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An investigation of creep in light metal alloys.

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THE INVESTIGATION OF CREEP IN LIGHT METAL ALLOYS

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ABSTRACT

An investigation was made of the creep characteristics of two aluminum alloys, 75S-T6 and 25S-T6, and one magnesium alloy, FS-1, under the conditions of high temperatures and high stresses. These alloys were selected as being representative of the light alloys in current use in the aircraft industry.

This investigation was divided into three phases: (1) "fast-rate" deformation under tension, (2) creep of short columns in compression, and (3) lateral deflection creep of columns. This thesis encompasses only the first phase of the investigation. The other phases are covered by current theses by the author's co-workers.

It was found that the aluminum alloys tested were superior in creep resistance to the magnesium alloy at the common temperatures used, 450°F and 500°F. However, the comparative creep resistance of the aluminum alloys was dependent upon the temperatures at which the alloys were compared: 75S-T6 being superior at 450°F, 25S-T6 at 500°F, and neither alloy superior to the other at 550°F.

The possible use of the alloys tested for short duration under conditions of high temperatures and high stresses is noted.

The data obtained is presented in both tabular and graphic form with various cross-plots provided for the purposes of cross comparison and to permit easy reference for obtaining given creep characteristics of the alloys tested.

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I. INTRODUCTION

Due to the tremendous speeds now attained by airplanes and missiles, the engineer of today is becoming more conscious of that creep phenomenon, often referred to in the past as "fast-rate" deformation, which results from the conditions of elevated temperature and high stresses. This trend towards those aircraft and missile speeds at which aerodynamic heating will become a principal structural factor has brought about increasing interest in the properties of materials at elevated temperature. This is especially true in the field of propulsion where the engineers are always striving for higher operating temperatures in order to increase the efficiency of their power plants.

While in many cases, it has been possible to circumvent structural difficulties due to creep phenomenon at elevated temperatures by the use of a low working stress; this practice, in general, is not acceptable in the field of aeronautics due to the ever present desire for greater performance. Therefore, there is a need for the investigation of the effect of creep on structural elements at operating conditions which are a combination of high temperature and high working stresses, as this effect must be known in order to design minimum weight structures.

Thus, in designing minimum weight structures for conditions of high working stress and high temperature, it is necessary to know for a constant applied load the rate of deformation with time defined as the creep. The phenomenon of time-dependent distortion of metals under stress, known as creep, has been recognized and studied by scientists

and engineers for many years. As a result, a large volume of information covering the theory of creep and creep data is now available.

However, as of now, little experimental work has been done in the field of "fast-rate" deformation, nor in the fields of creep in compression or in column deflection. As a result, the primary purpose of this investigation was an attempt to study given light alloys in these fields. This thesis covers only that portion of the investigation of "fast-rate" deformation (tension): that is, creep of the given aluminum and magnesium alloys under conditions of high temperature and high stress. The effects of creep in the other fields of this investigation are covered in theses by this author's co-workers.[1,2]

With the increase of interest by the scientists and engineers in creep and its effects, Schwope and Jackson[3] made a survey of the field of creep and have summarized the existing theories relating to creep phenomena and the extent of the current knowledge on the subject. An extensive bibliography of published works in the field is also included. Nadai[4] has recently furthered the theoretical side of the study of creep with his formulation of analytical expressions for describing the influence of strain hardening, of the time rate of change of the flow resistance, and of recovery strains on the creep and relaxation of metals under uniaxial stress. Extensive investigations have been conducted with resultant controversial explanations, in an attempt to determine the physical nature of creep. Further interest is now being found in the effect of alloying elements on the creep properties of metals, especially at elevated temperatures. Sherby and Dorn[5] have recently indicated that creep and tensile data of alpha solid solution alloys of aluminum above 400°K. can be simply related by the

Zener-Hollman relation $\sigma \equiv \sigma(\dot{\epsilon} e^{\frac{\Delta H}{RT}})$.

This investigation was conducted at the Guggenheim Aeronautical Laboratory of the California Institute of Technology, during the school year, 1951-52, under the supervision of Dr. E. E. Sechler.

II. MATERIALS FOR TEST

In this investigation, it was thought desirable to select light alloys presently used by the aircraft industry. Therefore, with this view in mind, the materials finally selected were: 25S-T6* and 75S-T6* aluminum alloys and the FS-1** magnesium alloy. It was also further decided to investigate these alloys in commercial form.

The 25S-T6 aluminum alloy specimens were cut from a surveyed, forged propeller obtained from the Cooperative Wind Tunnel of Pasadena. It might be mentioned, however, that this propeller was never in use to the author's knowledge. The 75S-T6 aluminum alloy and the FS-1 magnesium alloy specimens were turned down from 5/8" round extruded stock.

The room temperature mechanical properties of these materials are given in Table I. The values obtained for the given mechanical properties are in fair agreement with nominal values for those properties. The room temperature properties of these alloys after exposure for a period of 50 minutes at a temperature of 550°F for the aluminum alloys and 500°F for FS-1 are also given in Table I. The tensile stress-strain curves from the above tests are given in Figs. 1 through 3. The tensile specimens for these tests were of the same type as those used in the following creep tests.

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* Aluminum Company of America designations.

** Dow Chemical Company designations.

III. EQUIPMENT

The testing machine used for these tests was a single-lever type machine, which maintained a constant load on the specimen. The details of the machine are shown in Fig. 4. The frame for the machine was constructed of mild steel to a specification of 60,000 pounds per square inch on the tensile specimen. The diagonal legs on the loading side of the machine were found necessary for stability under high loading conditions, as then the center of gravity moved outside the enclosed frame of the system and the stand became unstable. The lever arm was suspended from the top plate of the stand by means of an adjustable fitting, permitting approximately four inches of travel for proper adjustment of the specimen for height in the frame. The lever arm gave a ten to one ratio in the load applied to the specimen as against the weight required on the loading plate.

The three knife-edges, set in the lever-arm, served a two-fold purpose: first and foremost, they substantially assisted in the accurate alignment of the axis of the specimen along the direction of load - an important prerequisite for accurate creep measurement; and, second, they permitted an accurate determination of the mechanical advantage of the lever-arm.

The specimen screwed into an adaptor suspended from a knife-edge through a mechanical heat joint. The heat joint was originally thought necessary to prevent excessive heat loss, but is now believed by this author to have been an elaboration unnecessary for the temperatures required by this investigation.

The bottom end of the specimen, through another adaptor and

heat joint, was connected to a ball-seat joint in the bottom plate of the stand. The ball-seat joint insuring accurate alignment of the axis of the specimen along the direction of load.

The construction of the adjustable fitting, by means of which the lever arm was suspended from the top plate, restricted the loading plate to a travel of 11.75 inches, permitting a maximum total elongation of the specimen of 1.175 inches. This elongation was found sufficient for the purpose of this investigation, though it did not permit the procurement of data on time to rupture under the conditions of test.

For obtaining the required elevated temperatures, a furnace was designed to be mounted about the specimen as shown in Fig. 4 and 5. The furnace was mounted vertical on a wooden platform laid between angle-irons on each side of the stand. It was hinged along a vertical diameter and swung open as indicated in Fig. 5.

The furnace tube was constructed in two halves of nine inch (O.D.) transite asbestos piping. This piping was then lined, to within an inch of both top and bottom of the tube, with a heat-resistant, polished steel liner, used as a reflector plate. An outer 24ST aluminum covering,thirteen inches in diameter, was encircled about each half of the transite tube. The spacing between the outer covering and the transite tube was then heavily packed with rock wool. A similar two-inch insulated spacing was provided for both the top and bottom of the furnace tube. The top and bottom of the furnace were then protected by a 1/3" steel plate. The two halves were connected by means of a vertical hinge along the entire heighth of the furnace, being held closed when shut by means of two snap fasteners diametrically

opposite to the hinges. The details of the furnace construction are given in Figures 6 through 9.

The heating elements consisted of sixteen vertical elements, equally spaced about the inner circumference of the furnace tube. These elements were combined into four coils, each consisting of four successive elements: two coils in each half.

Three settings were provided for controlling the temperature of the furnace: high, medium, and low. On the high setting, the maximum current consumption of the furnace was obtained, 2,000 watts/hr.; on medium setting, 1,000 watts/hr.; and on low setting, 500 watts/hr. On either the high or low setting, all coils operated: being connected in series for the low setting and in parallel for the high setting. On the medium setting, one pair of diametrically opposite coils were connected in parallel.

In addition to the permanent heating elements described above, it was necessary to install a temporary 185 watt coil in the bottom of the furnace tube. This coil was connected to two terminals installed on a quarter inch asbestos sheet which was then placed in the bottom of the furnace tube. As a result, it was most convenient to connect the temporary coil directly into the line (not through the furnace control), so that it operated at all times.

The power for the furnace was led through a breaker switch to a power relay, except for the temporary coil - the power for which was taken from the breaker switch directly. The temperature control was maintained by an automatic controlling pyrometer.

The creep strains were procured by means of two, eight-power telescopes, permanently mounted four inches apart on the side of

the furnace. The details of the mounting are shown in Fig. 8 and 9. The light source for the telescopes was introduced through a one inch hole, centered between the telescopes and passing entirely through the telescope mounting and the furnace insulation. The light source consisted of a 15 watt, 110 volt bulb mounted on the end of a plastic cylinder, fitted to the hole above. This permitted removal of the light source whenever it was found desirable or necessary.

The telescopes, permanently mounted as described above, were focused on two separate scales which were mounted on the specimen. The details of the scales are shown in Fig. 10. This method of mounting of the telescopes gave two fixed parallel lines of sight for reference in the measurement of the creep strains.

The scales were attached to the specimen four inches apart: this distance determining the gage length on the specimen for the test. The relative movement between the two scales, measured by the movement of each scale past a fixed line of sight on one of the telescopes, determined the deformation of the specimen.

A positive-motion screw type jack was used in loading the specimen: this type of jack permitting the most even and uniform application of the load.

The eight-power magnification of the telescope permitted estimations to 1/10 of the smallest dimension of the scale; thus, strains were detectable to approximately 0.00025.

The details of the creep specimen are given in Fig. 11. The gage section was 4 inches long and 0.375 inches in diameter.

IV. EXPERIMENTAL TECHNIQUE

The equipment as assembled is shown in Fig. 4 and 5.

The initial phase of the investigation was concerned with the calibration of the furnace and its control to attain the temperatures desired, maintaining a satisfactory temperature gradient across the specimen and a minimum variation of temperature of a specified point.

It was during this phase that it was necessary to add the temporary coil at the bottom of the furnace tube in order to attain a permissable satisfactory gradient across the gage length of the specimen. The addition of this coil reduced the gradient across the specimen from $\pm 11^{\circ}$ to $\pm 3^{\circ}$ at 550°F.

(With the results found above in mind, similar coils were permanently installed in both top and bottom of the furnace tube of the furnaces later completed for the compression and column testing. These furnaces also attained a temperature gradient across their specimens of $\pm 2^{\circ}$. This, however, may well have been due to the much greater mass of metal in the furnace tube in the other tests, as both the compression and the column deflection tests used a 3 pound steel cage for reversing the applied tension load of the machine to compression loading of the specimen.)

For calibration of the furnace, thermocouples were attached at both ends and at the center of the gage length of a specimen. The thermocouple, leading to the automatic controlling pyrometer, was attached to the top adapter. (The controlling thermocouple was then kept in this position for the subsequent tests). The temperature control setting was then varied to attain the desired testing temperature

at the center of the specimen, the temperature setting of the controlling pyrometer then being noted and the gradient observed.

It was found that this method of temperature control was very inadequate, as it was nearly impossible to reproduce a given setting of the spring loaded needle by means of which the temperature of the controlling pyrometer was controlled. Therefore, a thermocouple was placed at the center of each test specimen in order to assure that each test was on temperature. Further, the lack of a finer adjustment control for temperature made it necessary to accept a variance of $\pm$ 1.5°F from a desired temperature. However, the greatest error due to temperature control was probably the $\pm$ 3.5°F cyclic temperature variation which occurred at any given point in the furnace. This final cyclic variation of temperature at a given point was then only attained after many trials and adjustments of the automatic controlling pyrometer, being reduced to the above figure from an initial variation of $\pm$ 7-1/2°F. (Again this difficulty was not later encountered in the compression and column tests, probably due to the much greater mass of metal in the furnace tube during these tests.)

It was initially desired to set-up a definite set of tests for each temperature and each alloy, basing these tests on the tensile properties at elevated temperatures for these alloys as given in Fig. 12 and 13. However, the stresses obtained from Fig. 12 and 13 were not definite enough to permit such a program to be attempted. Therefore, the tests finally developed as a result of trial and error loadings, using the curves at elevated temperatures as a basis for making a judicious choice of the loading for the first run at each temperatures. Then appropriate tests were made at each temperature to obtain the

necessary data to provide a clear picture of the creep at the given temperature.

The alloys were tested in the following order: 75S-T6, 25S-T6, and FS-1. It had originally been planned to include the magnesium alloy ZK-60 in this set of tests. This was found impossible due to time requirements on the completion of the tests.

The procedure in setting-up a test was standardized and then followed as closely as possible. The threads of the specimen were first lubricated with Molycote, mixed with machine oil. This was necessary to prevent severe binding upon attempting to remove the specimen from the adaptors after a test.

The specimen was then placed in the adaptors and positioned properly in the furnace by adjustment of the height of the jack. The maximum height of the jack being used for the initial setting, at which the lever arm was positioned slightly above the horizontal.

The scales were then placed on the reduced section of the specimen, being carefully spaced four inches apart: this spacing determining the gage length on the specimen. A thermocouple was attached to the middle of the specimen between the scales to permit checking of the temperature during a test. The temperature was generally checked three or four times during each test and regulated, as necessary, to try to maintain the desired temperature for testing.

That half of the furnace having the telescope mounting was then positioned. The telescopes were focused on the scales which were turned about the specimen so as to be centered in the field of the telescope. The furnace was then closed and the position of the scales again checked through the telescopes. Due to the extremely small

field of the telescopes, the above process was found to be most exacting as any small movement of the furnace or the system often caused the scales to pass from the field of view. Then, the positioning process would have to be repeated.

The load was then applied to the system and the positioning of the scales checked. The loading of the system was often found to twist the system sufficiently to cause the scales to turn out of the field of the telescope. As a result of this, the system was kept under a slight tension at all times once it was aligned. This was done by finger-tightening of the ball-seat joint in the bottom plate of the stand. The resulting tension on the system was negligible compared to the final loads applied, and this method merely induced small errors in the initial strains at the time of test. This initial load had no effect on the creep once the test began.

Once the system was properly aligned, a reading of the scales was taken and recorded. The furnace control was then set on "high" until the temperature for test was attained. This time varied from six to twelve minutes dependent upon the temperature for the test and how much the furnace had cooled from the previous test. Upon attaining the temperature for test, the furnace control was then set on "low" as it was found that this setting gave a more uniform heat throughout the furnace with the smallest variation of temperature at any point over the gage length of the specimen. The specimen was then soaked at temperature for approximately fifty minutes (total length of test - one hour). During this entire heating period, a slight tension was maintained on the specimen.

Upon completion of the heating period, an unloaded reading of

the scales was taken. The load was then smoothly applied and the test run. Readings were taken every fifteen seconds during the test.

V. RESULTS AND DISCUSSION

All the experimental data obtained were plotted originally as Time vs. Deformation. Thus, Fig. 14 through 16 give the results of the test of 75S-T6 at the chosen temperatures; Fig. 17 through 19, the results from 25S-T6; and Fig. 20 through 22, the results from the magnesium alloy, FS-1.

On these figures giving the data as obtained, there is an inconsistency in the deformation intercept of the curve at time zero. In general, there appears to be a tendency for an increased intercept with an increased stress. This is especially true of the magnesium alloy and the aluminum alloy, 25S-T6. This inconsistency in the deformation intercept at zero time is probably a direct result of the testing technique. As reported in the procedure for testing, these tests were made with the specimen under a slight tension during the heating period (to maintain the scales in the field of the telescopes). This resulted in a variation of the stress applied to the specimen during the heating period. Further, any variation in the rate of loading of a specimen during a test would affect this intercept. And as this was done manually, some variations undoubtedly existed from test to test. Therefore, though these variations in the testing technique were kept as few and as small as possible, their existence might well explain any inconsistency in the deformation intercept.

As a result of this inconsistency in the intercept, the curves above were replotted as Strain vs. Time with all intercepts being moved to the origin; i. e., zero strain at zero time. In these curves, the zero-time strains were neglected to permit better comparison of

the resulting creep curves at a given temperature. The results of the replotting of the initial curves are given by Fig. 23 through 31.

On these figures, the minimum creep rates as obtained for each stress are noted. The characteristics of these creep curves are essentially those found for most alloys when tested under constant load. In general, a primary, secondary, and tertiary stage of creep are noted. But as the stress increases for a given temperature, the minimum or secondary creep rate as well as the duration of each stage are all varied appreciably. The variations in the creep characteristics of these alloys with varying stress at a given temperature are shown by cross-plots of Fig. 23 through 31.

All the important creep characteristics for these alloys can be found from the above two sets of curves. Thus, the initial creep strain ε_0 (total strain at zero time) and the secondary or minimum creep rate $\dot{\varepsilon}$ are recorded in Table II. One desirable characteristic could not be determined during these tests - time to rupture - since the testing machine did not permit sufficient elongation of the specimen for rupture. The cross-plots mentioned above are for the purposes of cross comparison and to permit easy reference for a given characteristic of the alloys.

A study of the above figures, together with those of Fig. 32 through 38, show the aluminum alloys to have superior creep resistance to the magnesium alloy, FS-1, at the common temperatures at which they were tested. Further, between the aluminum alloys, 75S-T6 is found to be superior at 450°F, but 25S-T6, superior at 500°F; and, at 550°F, there is little difference between the two alloys.

The different scales on which the aluminum and the magnesium alloys are plotted is to be noted: this difference being the result of the difference in the nature of creep in the two different alloys at these temperatures. The aluminum alloys, in general, exhibited a much lower minimum creep rate at the higher stresses, with a sharply appearing tertiary stage. Once the tertiary stage was developed, the rate of deformation was too rapid to permit readings to be taken. Further, it was noted that the aluminum alloys had approached their maximum elongation at these temperatures: approximately 1/3 of the specimens were broken by the tests and nearly all of the others evidenced a definite necking down region which occurs just prior to rupture. The magnesium alloy exhibited a much higher minimum creep rate under high stresses, but no sharply appearing tertiary stage was developed in so far as these tests could be carried on (limitation of the loading machine on the elongation attainable). No evidence of necking down of the specimen was noted of the magnesium alloy. As a result, readings of a much greater deformation (limitation of the machine) could be taken of the magnesium alloy.

The magnesium alloy was readily oxidized at the temperatures of this investigation, so that any effect of such surface phenomena on the creep resistance of a metal must be recognized as existing during these tests. However, no attempt is made to differentiate such effects in the data obtained. No such oxidation tendencies were found for the aluminum alloys.

Fig. 32 and 33 are cross-plots of Minimum Creep Rate vs. Stress. These figures most readily indicate the comparison of the alloys as

given above. On Fig. 32, a discontinuity is noted in the curve for $400^{\circ}F$ at a stress of 12,000 psi. This point was checked and found correct, and, as no time for further checking was available, the discontinuity remains. A similar discontinuity is found on Fig. 35, which may well indicate that the stress of 13,000 psi is in error.

Fig. 34 and 35 give cross-plots of Stress vs. Transition Time wherein transition time is defined as that time at which the creep rate increases over that of the secondary or minimum creep rate. The above two sets of cross-plots give easy reference to these creep characteristics which are of the most importance to engineers.

Fig. 36 through 38 are cross-plots of Stress vs. Time for Percent of Creep. Creep of 2-1/2, 5, and 7-1/2 percent are plotted thereon for the temperatures tested.

VI. CONCLUSIONS

1. The aluminum alloys tested are superior creep resistant alloys to the magnesium alloy under conditions of high temperature and high stress. However, the comparative creep resistance of the aluminum alloys is dependent upon the temperature at which they are compared: 75S-T6 being superior at 450°F, 25S-T6 at 500°F, and both alloys being nearly the same at 550°F.

2. These alloys would be unsatisfactory materials for long time usage under conditions of high temperature and near ultimate stress. However, all the alloys tested might well be satisfactory for short duration usage at high temperatures and stresses within the range of values tested, provided the elongation which would occur under these conditions would not be a limiting factor; for example,

   a. a sudden manuevering load on an already heated missile,

   b. short time acceleration loads on heated engine and missile components.

VII. RECOMMENDATIONS

1. The effect of soaking time at temperature, under the condition of high temperature and high stress, on the resultant creep rate of metals should be carefully investigated, as this property would essentially be the limiting factor on the actual use of these metals under these conditions. Along this same line, the effect of shock loading of the metal in attaining high temperatures would be interesting.

2. Certainly, the study of the effect of the addition of alloying elements to improve the creep resistance of a basic metal is of major importance under the conditions noted herein.

3. For future investigations, it is recommended that the furnace be modified to insure the establishment of a more uniform temperature over the gage length of the specimen. This might easily be done by replacing the present vertical elements with three separate windings, covering the top, middle, and bottom sections respectively, the current through each section being adjusted independently to produce a uniform temperature on the specimen.

4. It is also recommended that the lever arm of the loading machine be modified to permit measurements of deformation to rupture, as time to rupture under these conditions should probably become of the more useful properties of any metal.

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TABLE I

ROOM TEMPERATURE MECHANICAL PROPERTIES OF TESTED ALLOYS

Alloy	Tensile Strength (psi)	Yield Stress (psi)	Elong. percent in 2 in.	Mod. of Elasticity (psi)
		Nominal Properties (No exposure)		
75S-T6	84,800	76,500	10.0	10.27×10^6
25S-T6	58,700	40,450	8.0	10.61×10^6
FS-1	39,452	29,500	8.9	6.56×10^6
		50 Minute Exposure		
75S-T6	39,250	17,700	10.0	10.27×10^6
25S-T6	31,598	12,600	15.5	10.61×10^6
FS-1	39,565	29,000	8.0	6.56×10^6

TABLE II

CREEP CHARACTERISTICS

Alloy	Temperature (^{o}K)	(^{o}F)	Stress (psi)	ε_o Initial Strain	$\dot{\varepsilon}$ Minimum Creep Rate (1 /hr.)
75S-T6	505	450	17,000	.00600	-------
			16,500	.00625	1.568
			16,000	.00750	0.600
			15,000	.00800	0.057
	533	500	12,000	.01050	-------
			11,500	.00750	2.445
			11,000	.00820	0.783
			10,500	.00725	0.528
			9,000	.00750	0.062
	561	550	9,000	.01000	2.843
			8,500	.01100	1.178
			8,000	.00950	0.680
			7,500	.00825	0.234
25S-T6	505	450	16,000	.00938	1.340
			15,500	.00850	0.480
			15,000	.00650	0.340
			13,000	.00662	0.042
	533	500	12,500	.00975	2.895
			12,000	.00925	1.339
			11,500	.00875	0.545
			11,000	.00812	0.357

Alloy	Temperature (^{o}K)	(^{o}F)	Stress (psi)	ε_o Initial Strain	$\dot{\varepsilon}$ Minimum Creep Rate (1 /hr.)
25S-T6 (cont'd)	561	550	9,000	.01150	3.285
			8,500	.01125	0.663
			8,000	.01050	0.423
FS-1	478	400	13,000	.02375	5.550
			12,000	.01788	5.175
			11,000	.01450	1.255
			10,500	.01125	0.878
			10,000	.00950	0.600
	505	450	10,500	.02975	6.660
			10,000	.01875	4.300
			9,000	.01300	1.555
			8,000	.01313	0.850
	533	500	8,500	.02275	5.205
			8,000	.01600	3.248
			7,000	.01775	1.320
			6,000	.01850	0.619

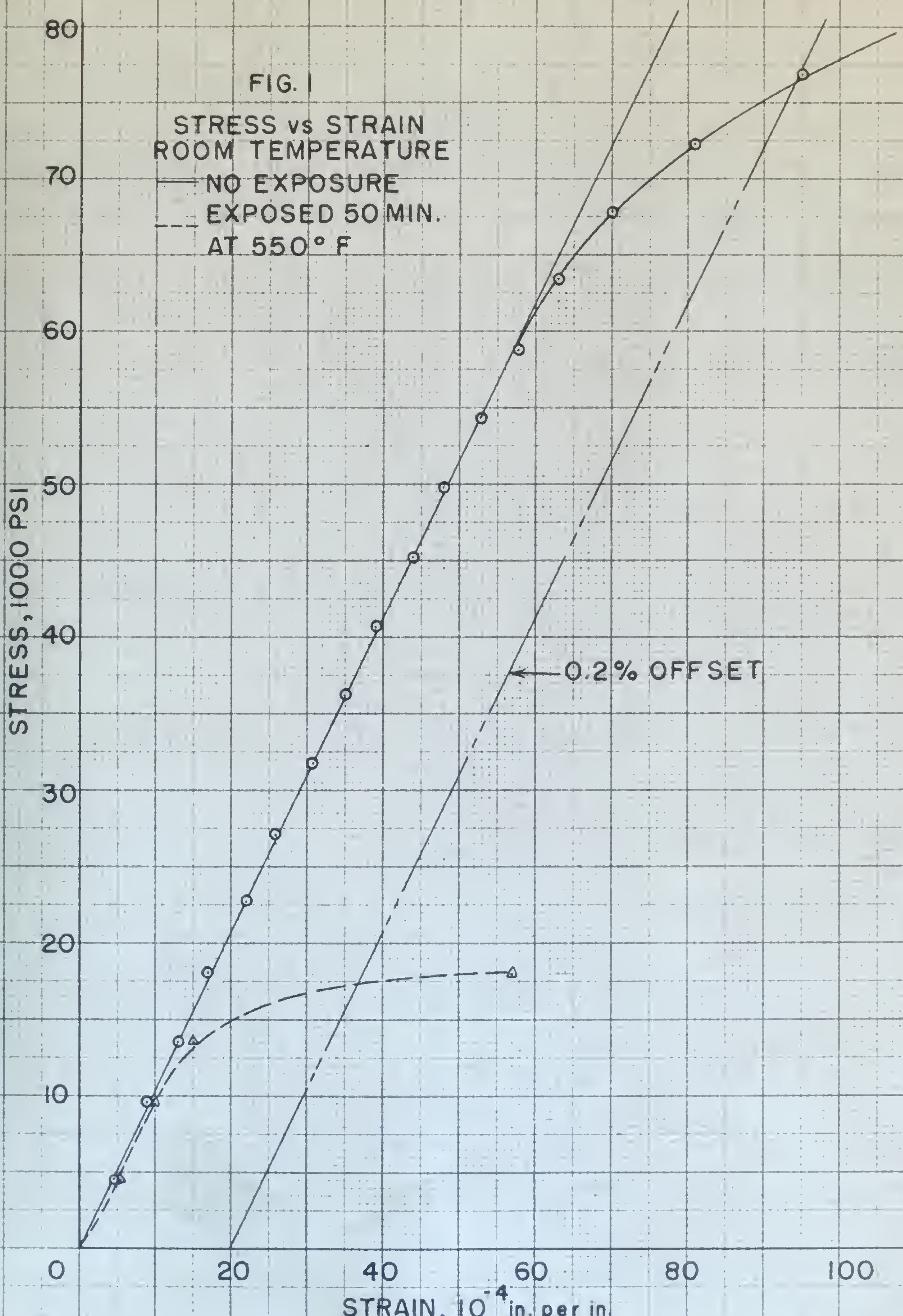


FIG. I
STRESS vs STRAIN
ROOM TEMPERATURE
NO EXPOSURE
EXPOSED 50 MIN.
AT 550° F
0.2% OFFSET
STRESS, 1000 PSI
STRAIN, 10^{-4} in. per in.
0
10
20
30
40
50
60
70
80
100

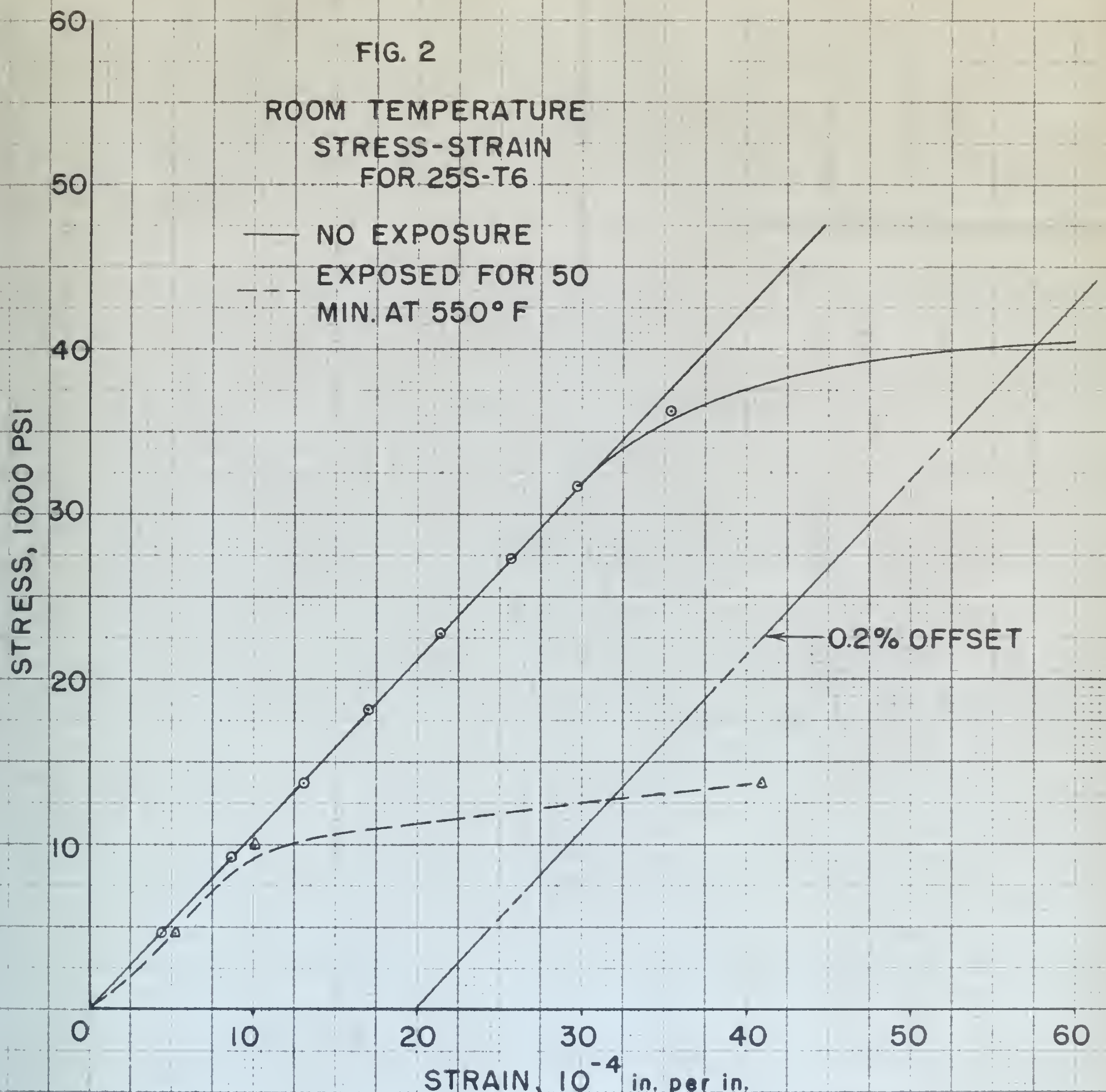


FIG. 2
ROOM TEMPERATURE
STRESS-STRAIN
FOR 25S-T6
NO EXPOSURE
EXPOSED FOR 50
MIN. AT 550° F
0.2% OFFSET
STRESS, 1000 PSI
STRAIN, 10^-4 in. per in.
0
10
20
30
40
50
60

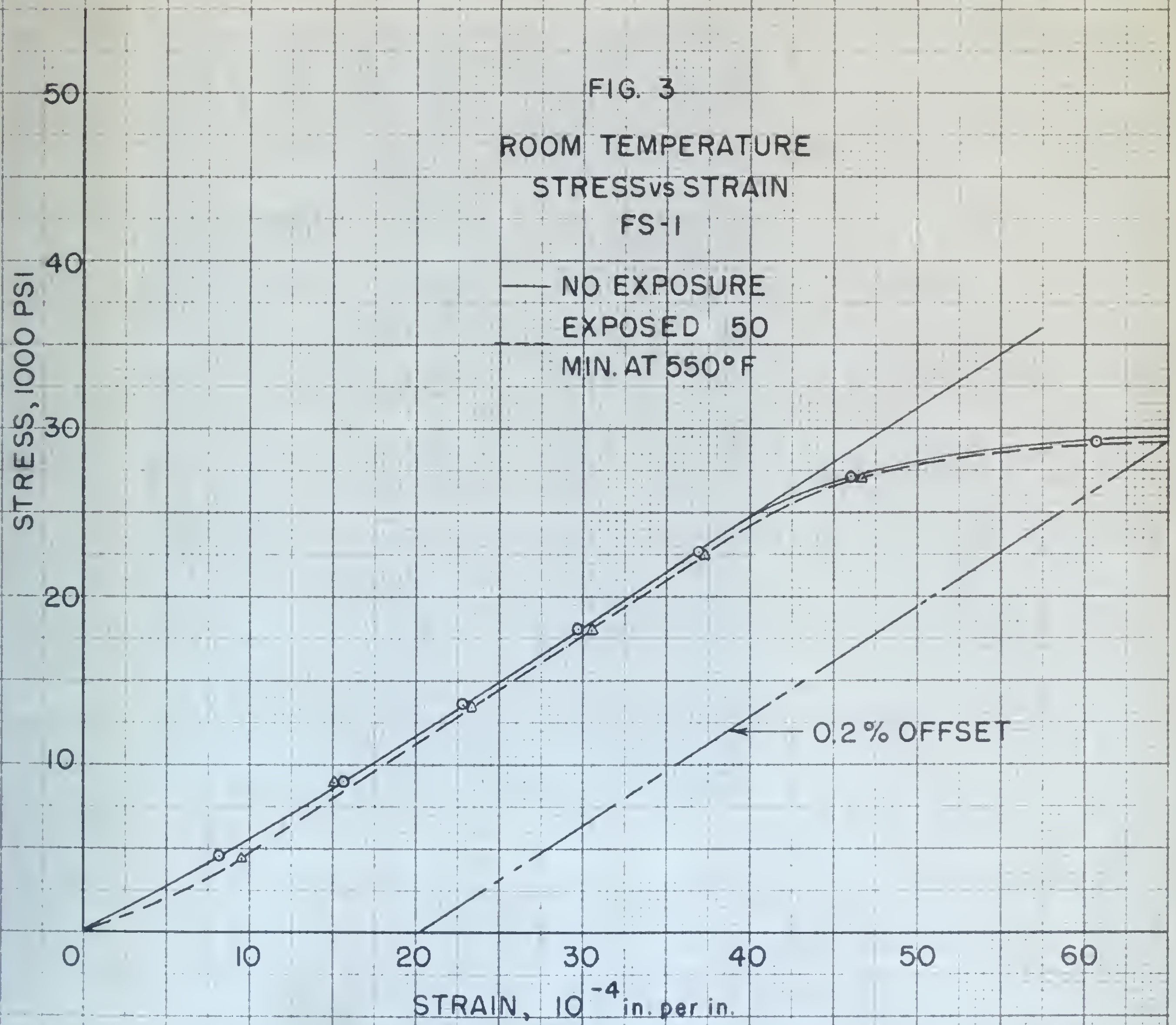


FIG. 3
ROOM TEMPERATURE
STRESS vs STRAIN
FS-1
NO EXPOSURE
EXPOSED 50
MIN. AT 550°F
0.2 % OFFSET
STRESS, 1000 PSI
STRAIN, 10^-4 in. per in.
0
10
20
30
40
50
60

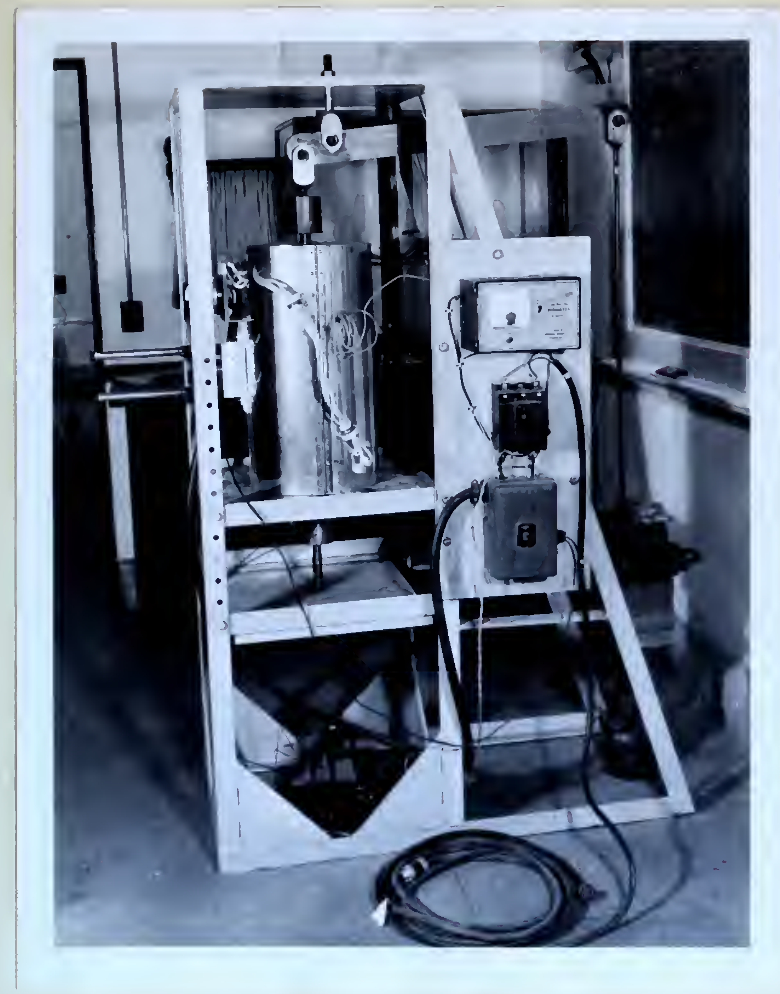


Fig. 4 Testing Machine

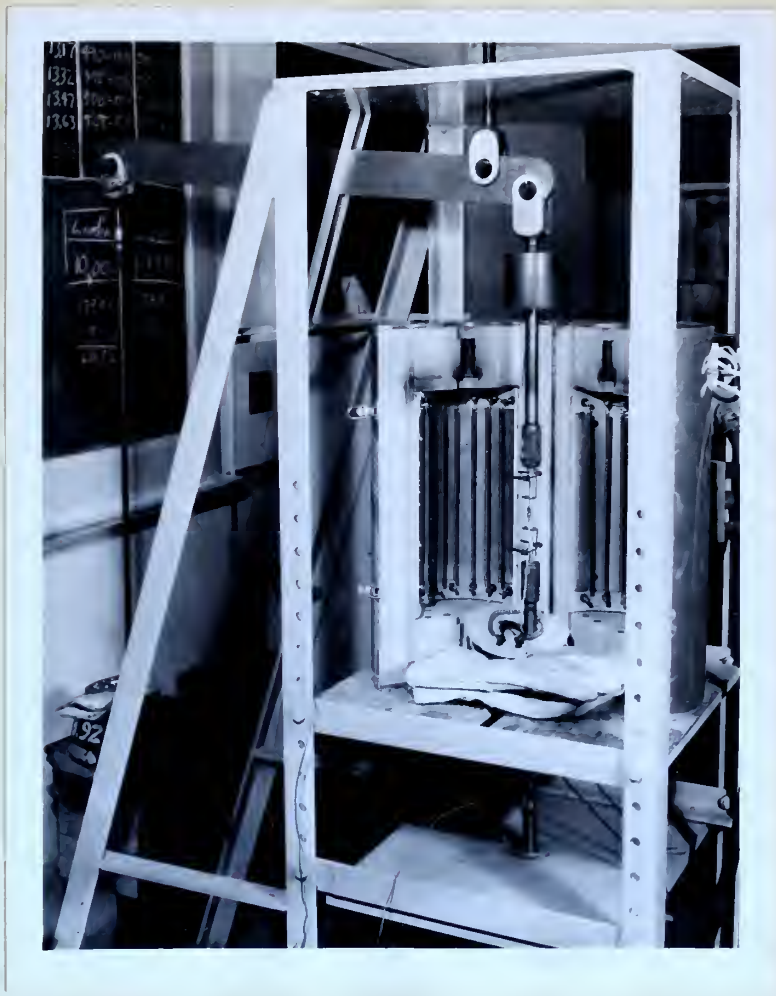
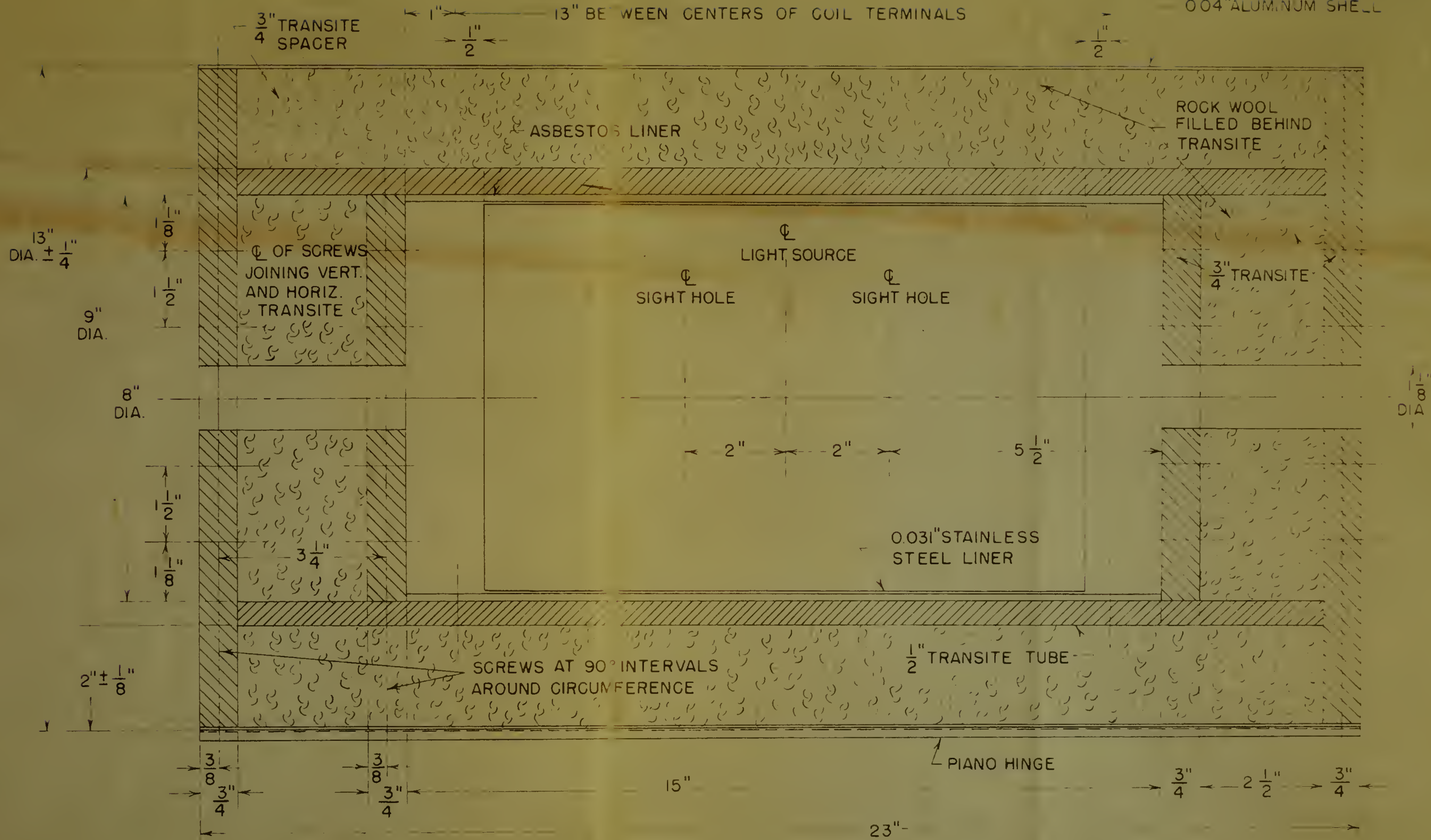


Fig. 5 Furnace Mounting

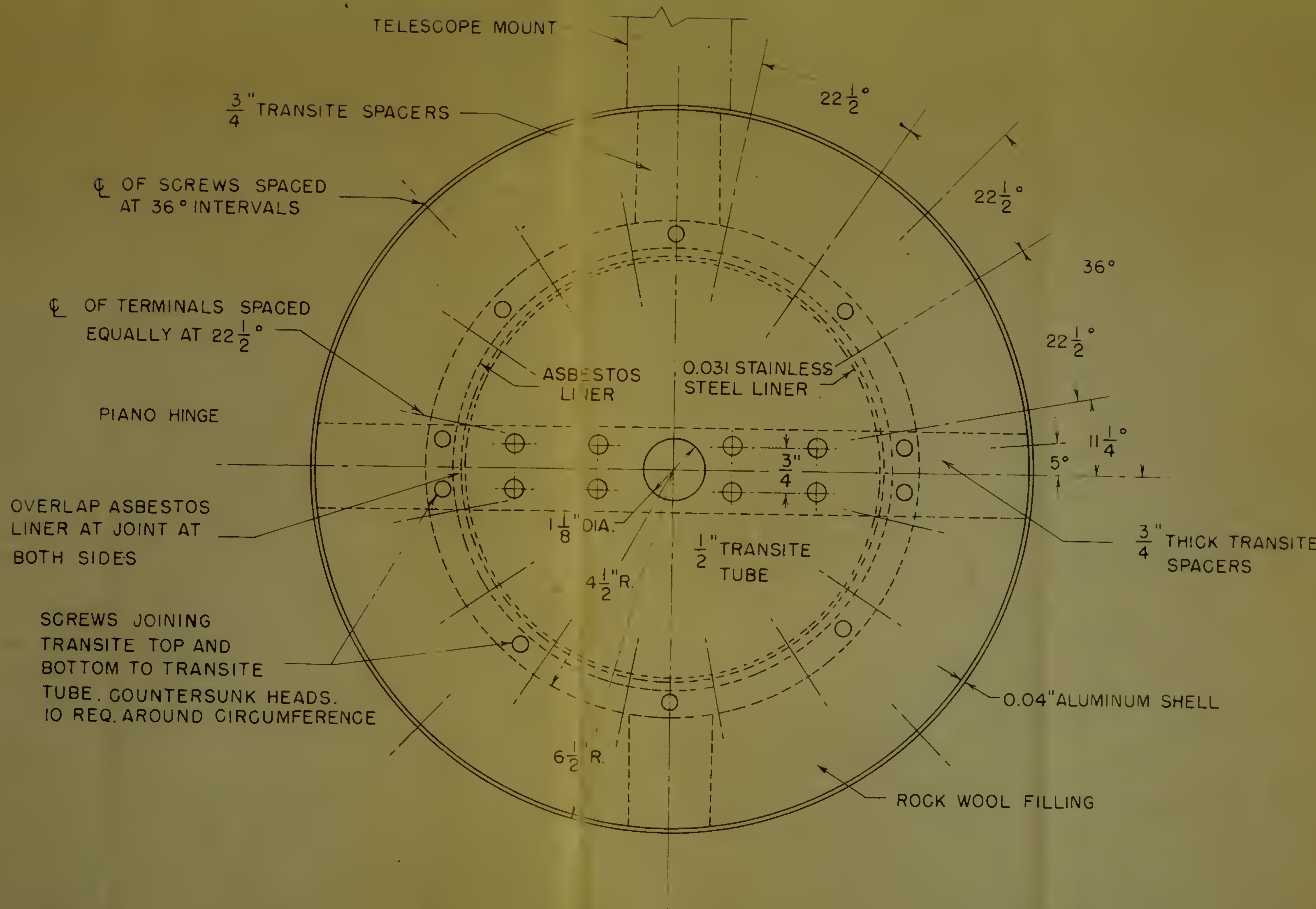


NOTES:

1. FURNACE TO BE BUILT IN TWO HALVES. USE $\frac{3}{4}$" TRANSITE SHEET AT DIVIDING LINE TO CLOSE IN ROCK WOOL FILLER.
2. STAINLESS STEEL LINER TO BE FITTED WITH OVERSIZE HOLES AT FASTENING POINTS TO ALLOW FOR EXPANSION.
3. MANNER OF SCREWING TRANSITE TOGETHER IS IDENTICAL AT TOP AND BOTTOM OF FURNACE.

FRONT VIEW
CREEP TEST FURNACE

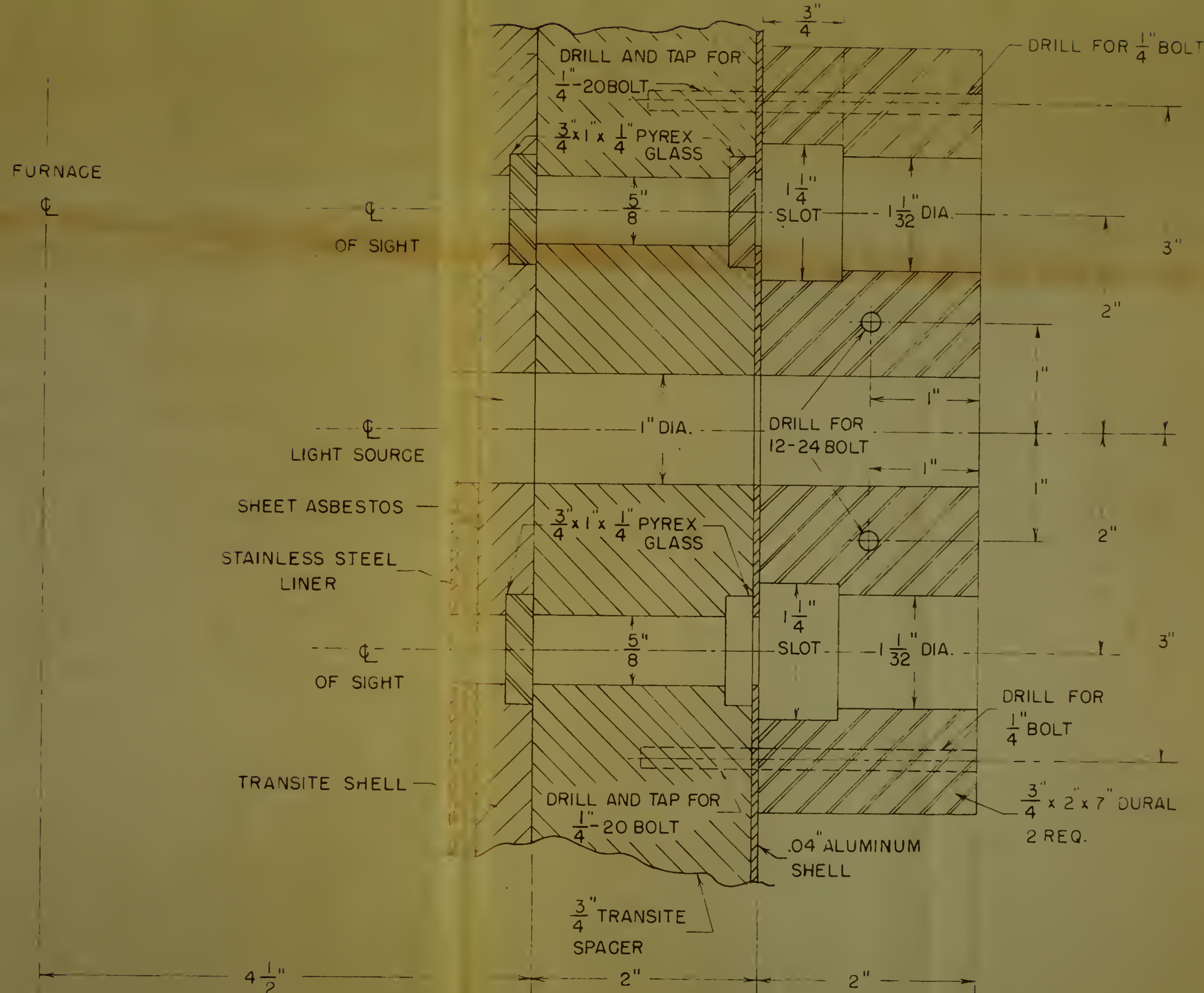
FIG. 6



TOP VIEW

GREE TEST FURNACE

FIG. 7



DET. OF WINDOWS AND TELESCOPE MOUNT
FOR CREEP TEST FURNACE

FIG. 8

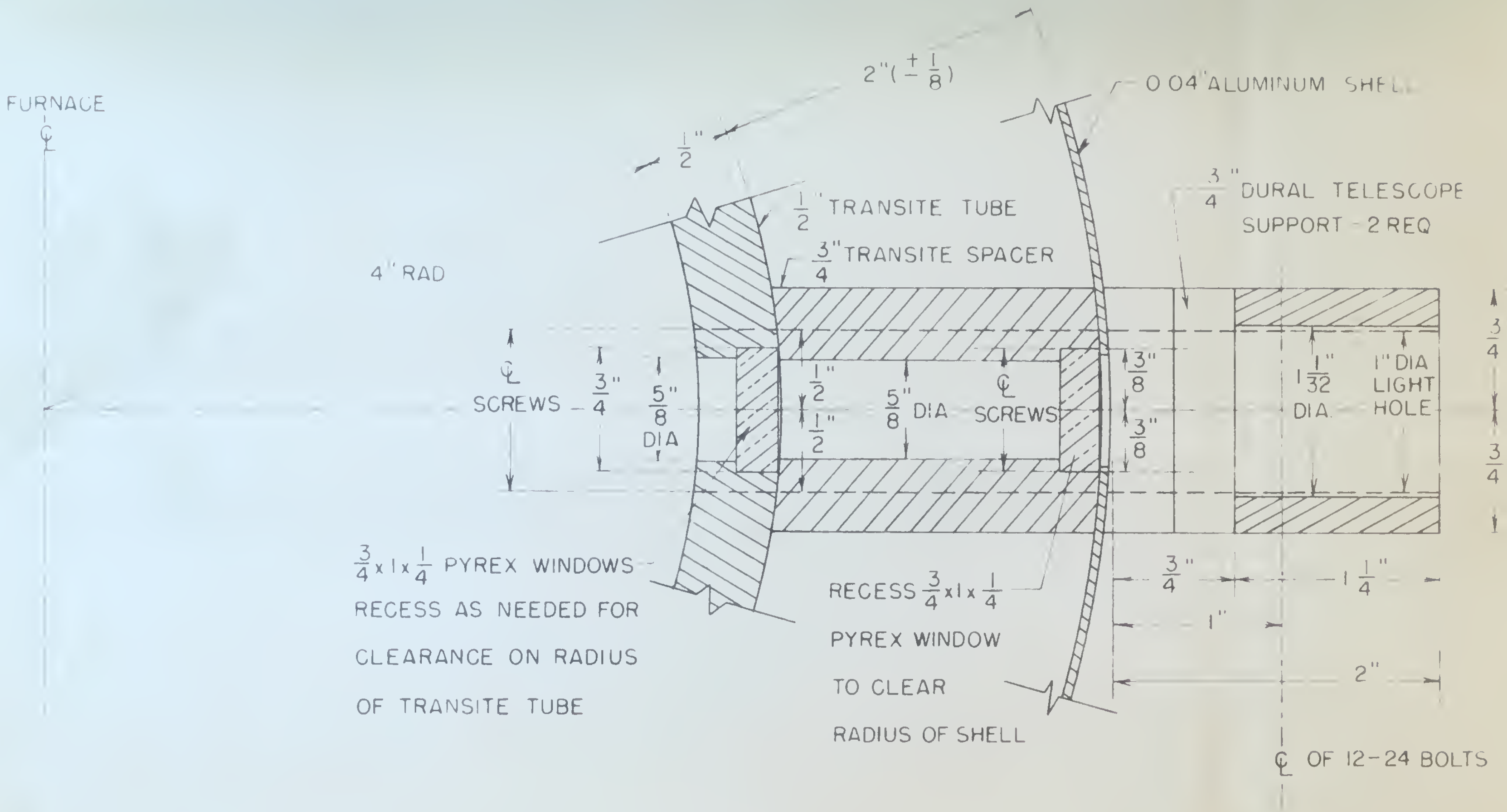
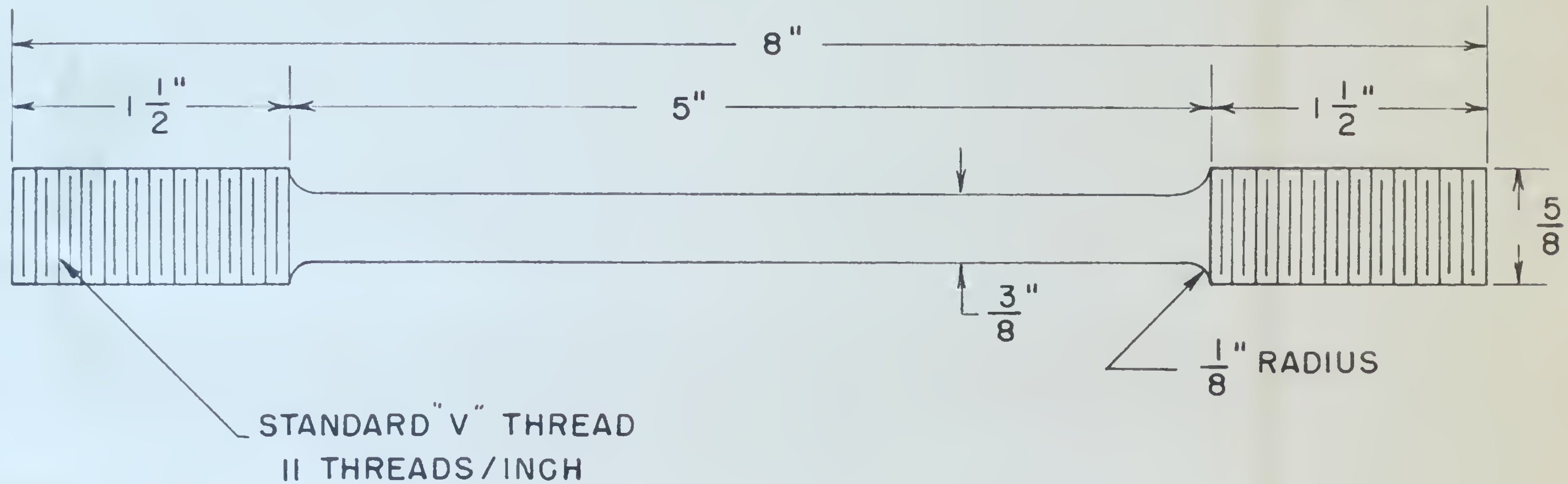


FIG. 9

HORIZONTAL SECTION THROUGH CENTER LINE OF TELESCOPE



CREEP TEST SPECIMEN (TENSILE)

FIG. 11

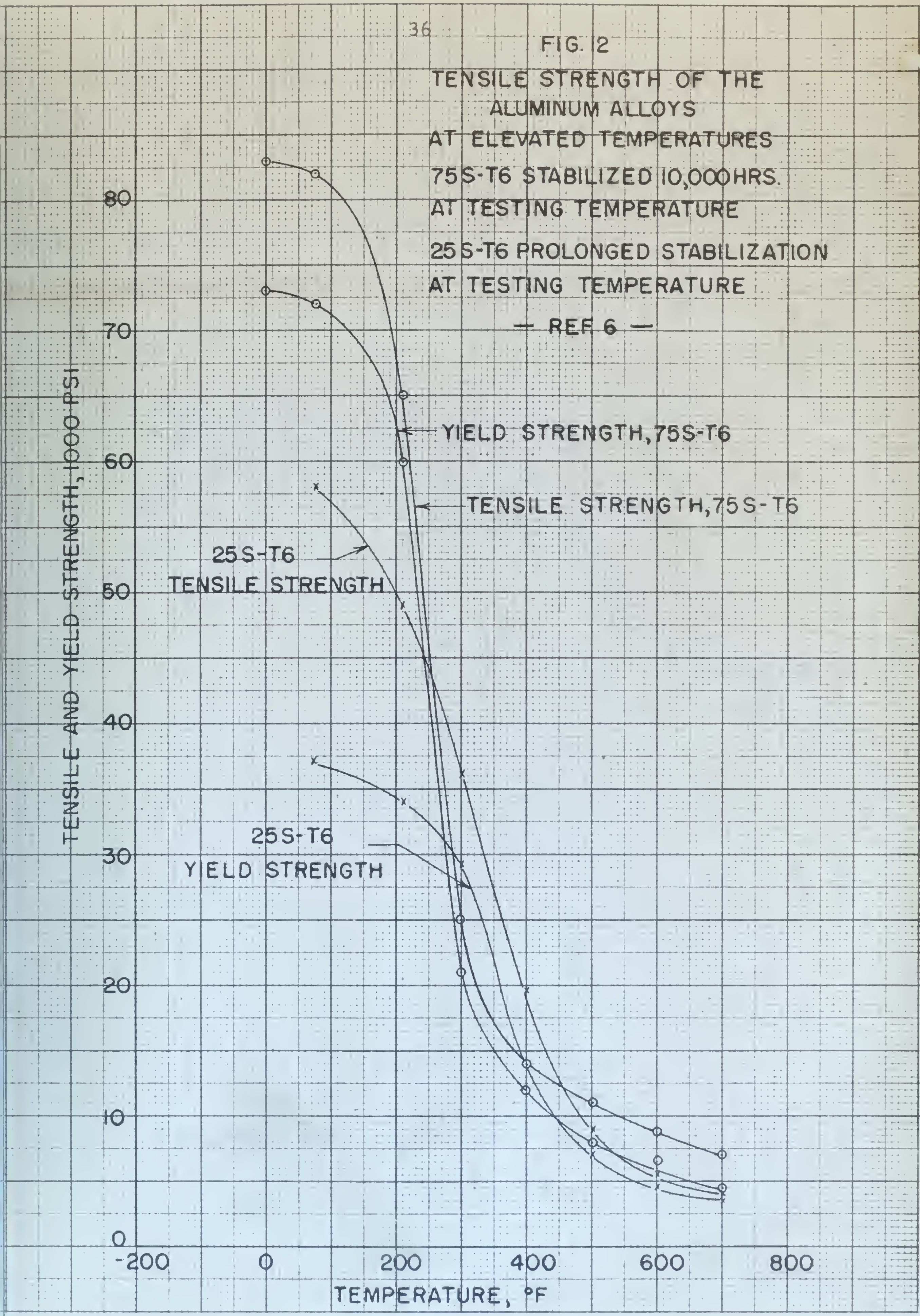


FIG. 12
TENSILE STRENGTH OF THE ALUMINUM ALLOYS AT ELEVATED TEMPERATURES
75S-T6 STABILIZED 10,000 HRS. AT TESTING TEMPERATURE
25S-T6 PROLONGED STABILIZATION AT TESTING TEMPERATURE
— REF 6 —
YIELD STRENGTH, 75S-T6
TENSILE STRENGTH, 75S-T6
25S-T6 TENSILE STRENGTH
25S-T6 YIELD STRENGTH
TENSILE AND YIELD STRENGTH, 1000 PSI
80
70
60
50
40
30
20
10
0
-200
0
200
400
600
800
TEMPERATURE, °F

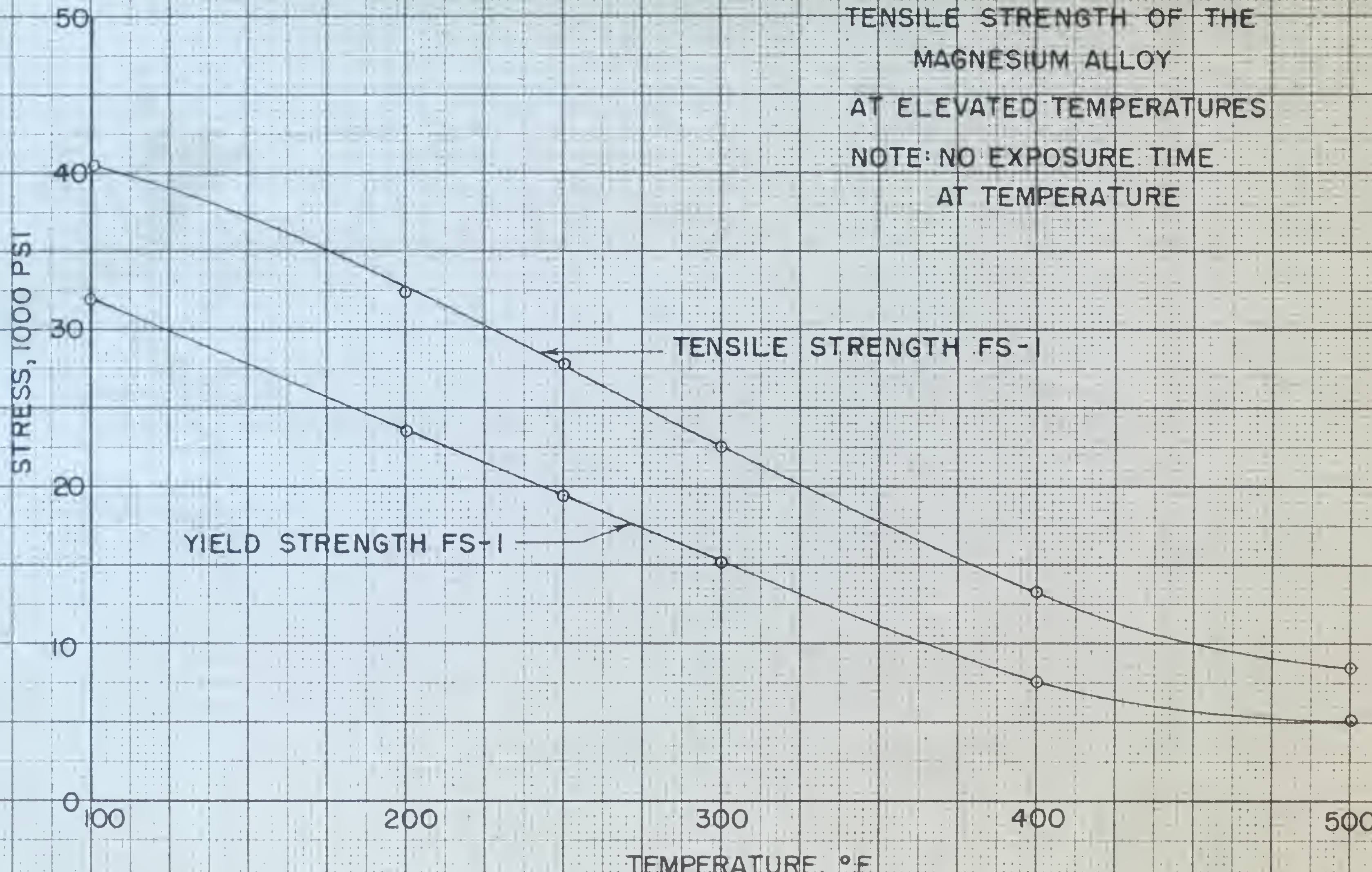


FIG. 13
TENSILE STRENGTH OF THE MAGNESIUM ALLOY AT ELEVATED TEMPERATURES
NOTE: NO EXPOSURE TIME AT TEMPERATURE

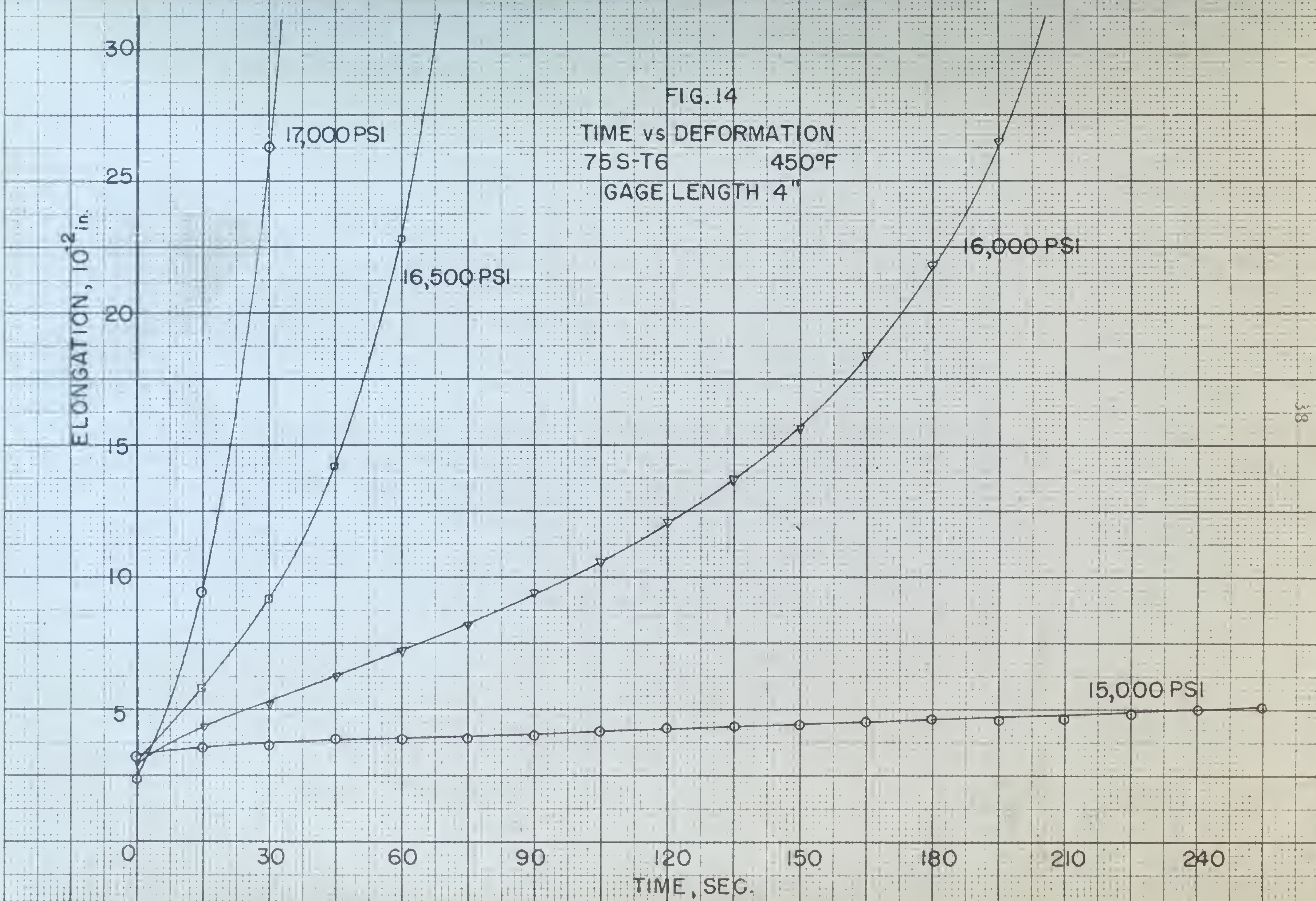


FIG. 14
TIME vs DEFORMATION
75 S-T6
450°F
GAGE LENGTH 4"
17,000 PSI
16,500 PSI
16,000 PSI
15,000 PSI
ELONGATION, 10^-2 in.
TIME, SEC.
0
5
10
15
20
25
30
0
30
60
90
120
150
180
210
240

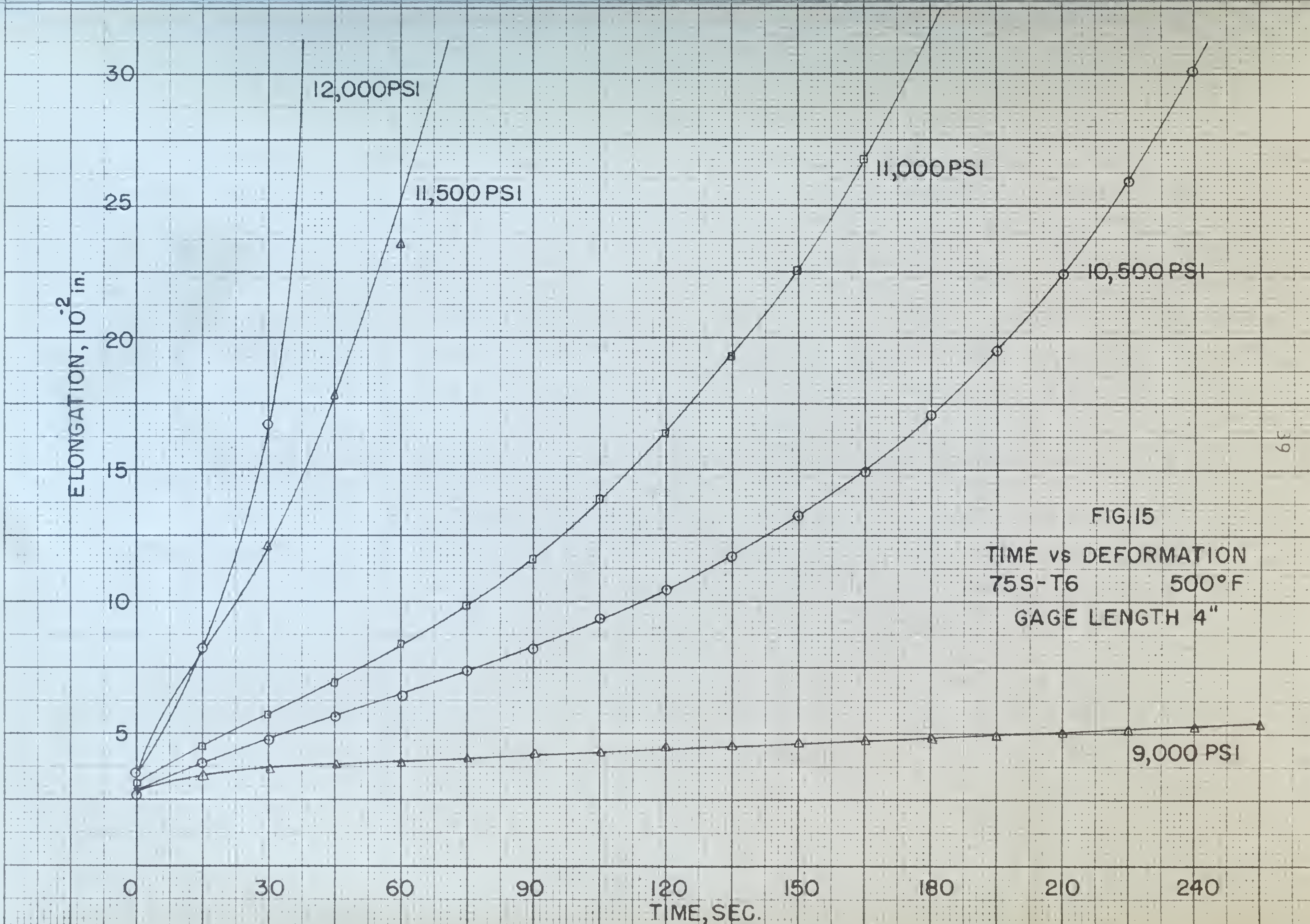


FIG. 15
TIME vs DEFORMATION
75S-T6 500°F
GAGE LENGTH 4"

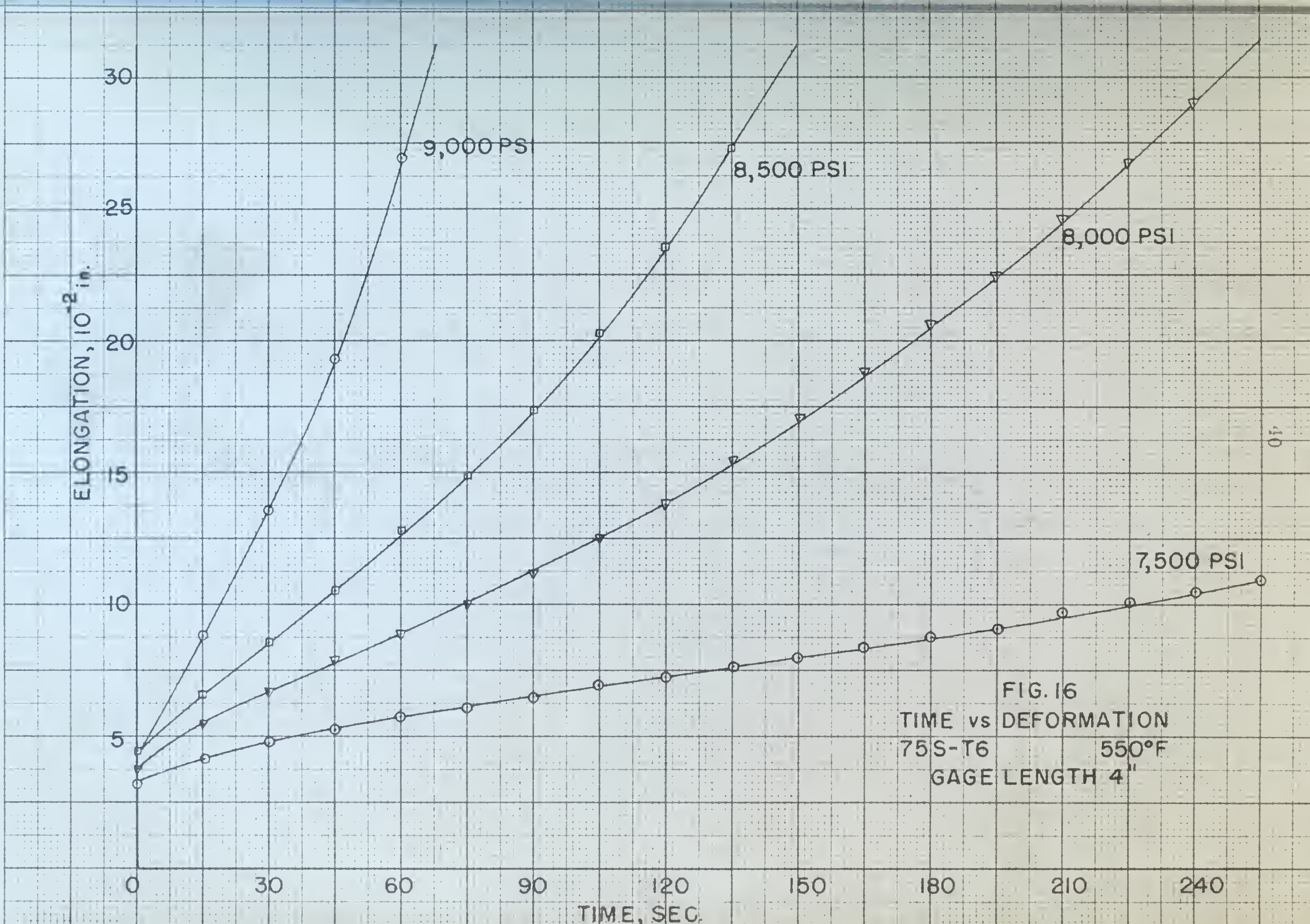


FIG. 16
TIME vs DEFORMATION
75S-T6 550°F
GAGE LENGTH 4"

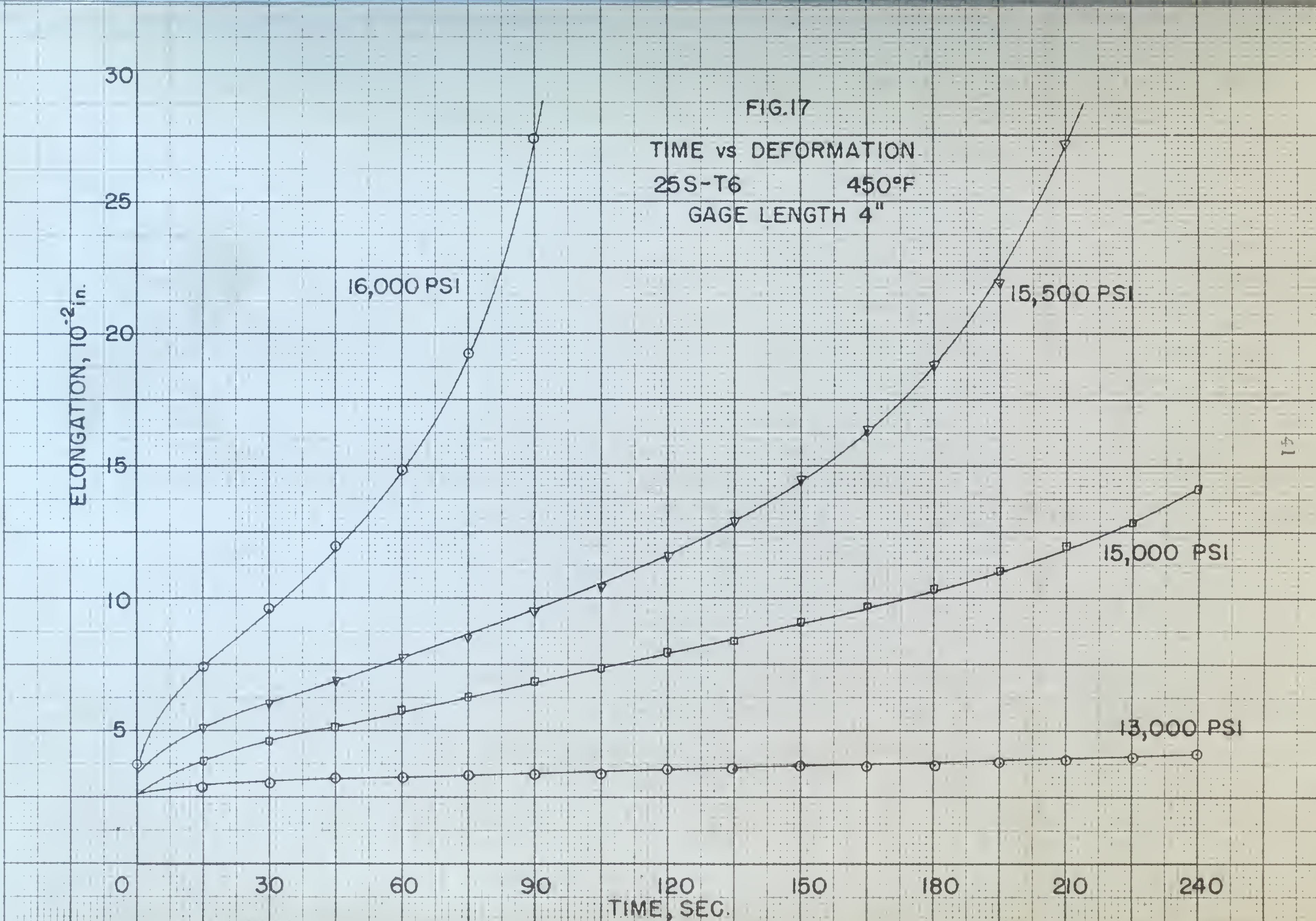


FIG.17

TIME vs DEFORMATION

25S-T6 450°F

GAGE LENGTH 4"

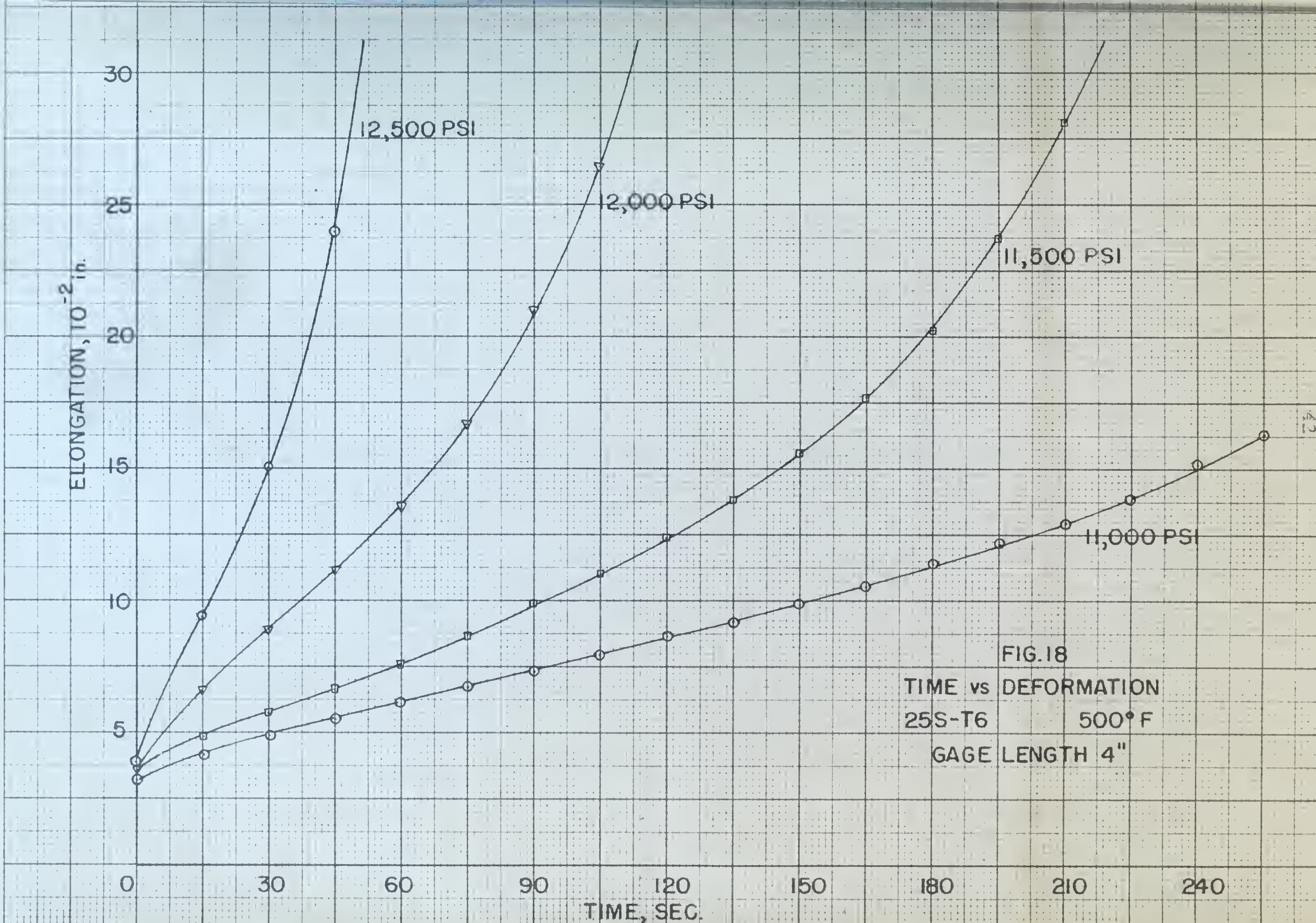


FIG.18
TIME vs DEFORMATION
25S-T6 500° F
GAGE LENGTH 4"

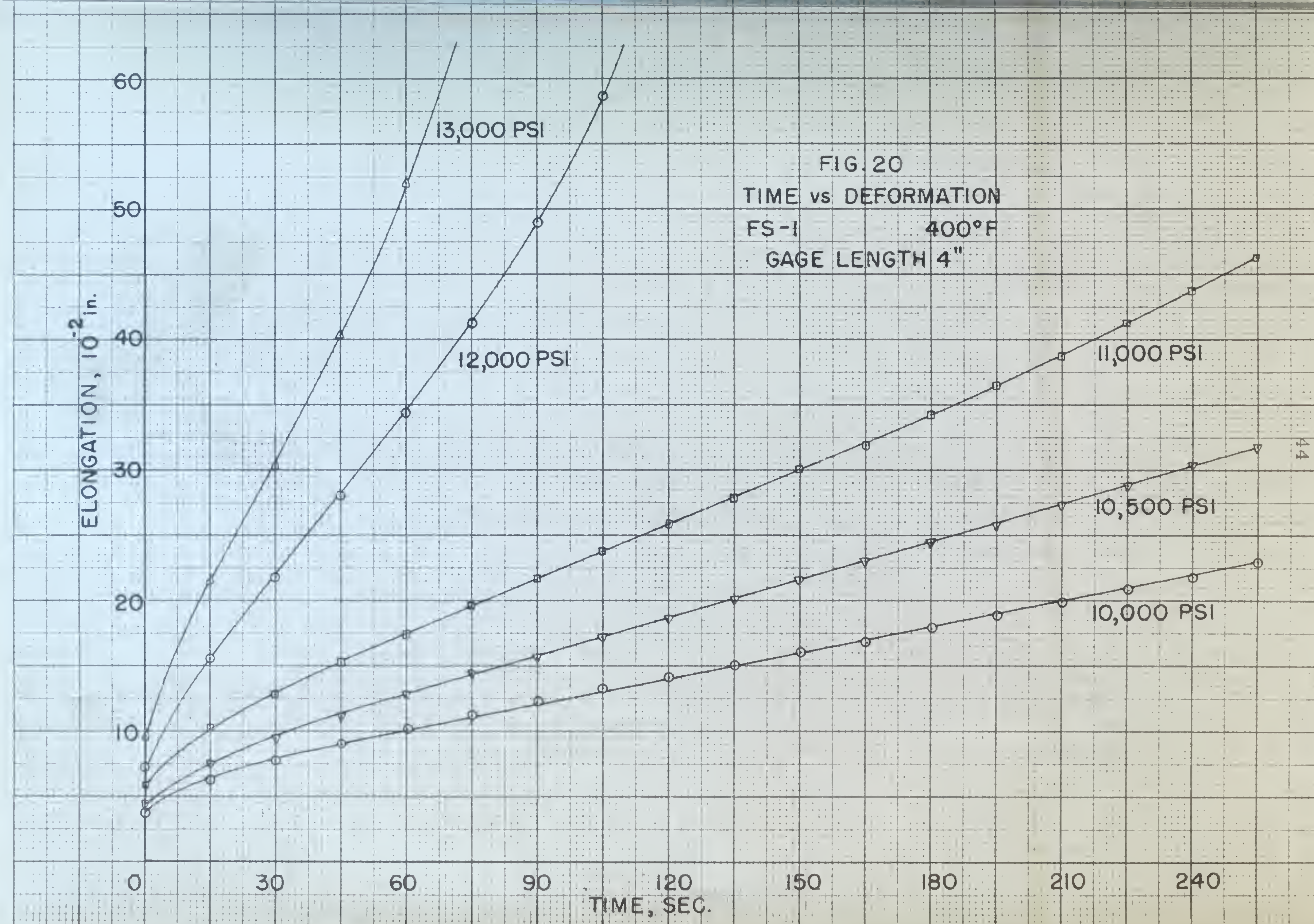


FIG. 20
TIME vs DEFORMATION
FS-1 400°F
GAGE LENGTH 4"

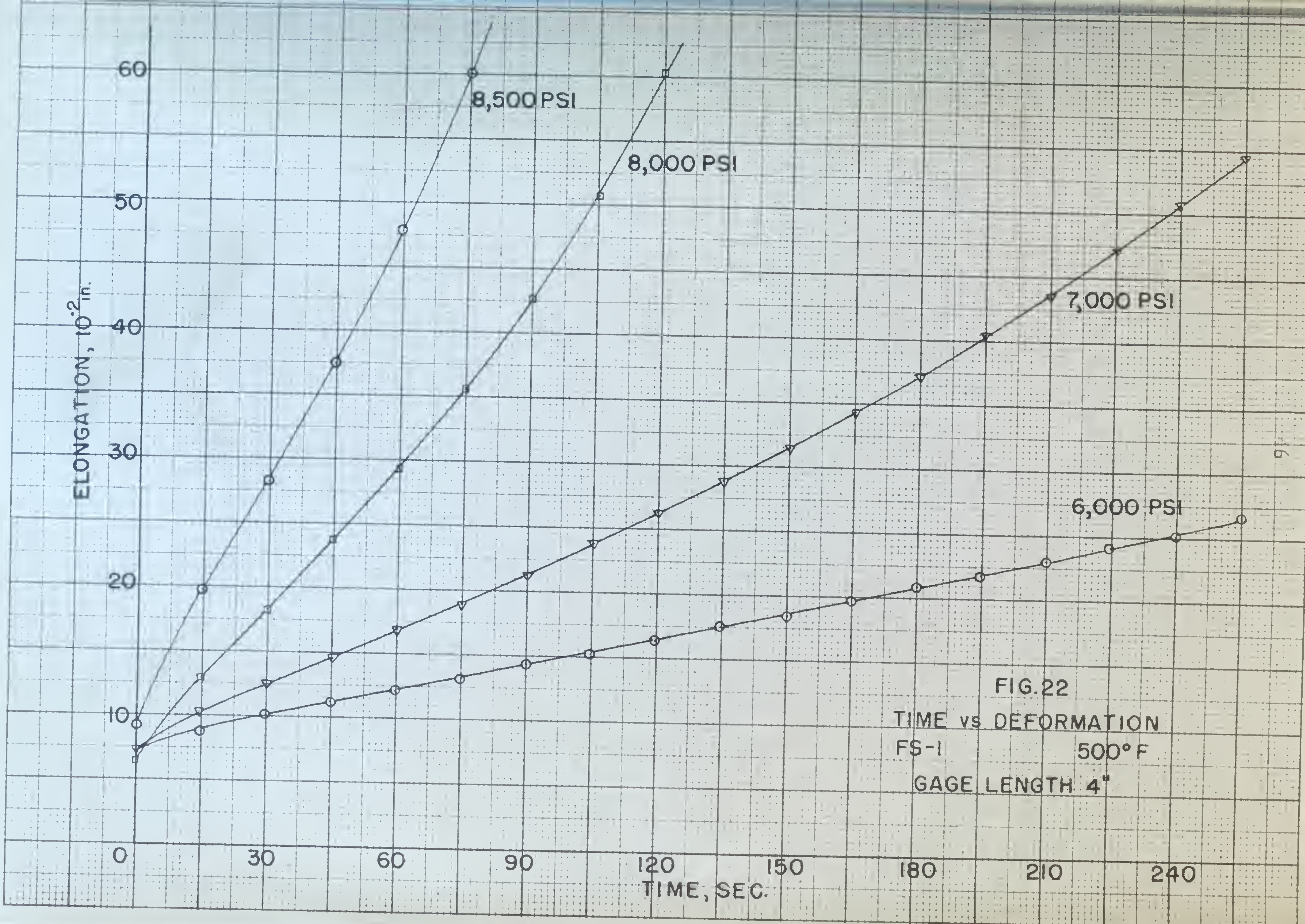
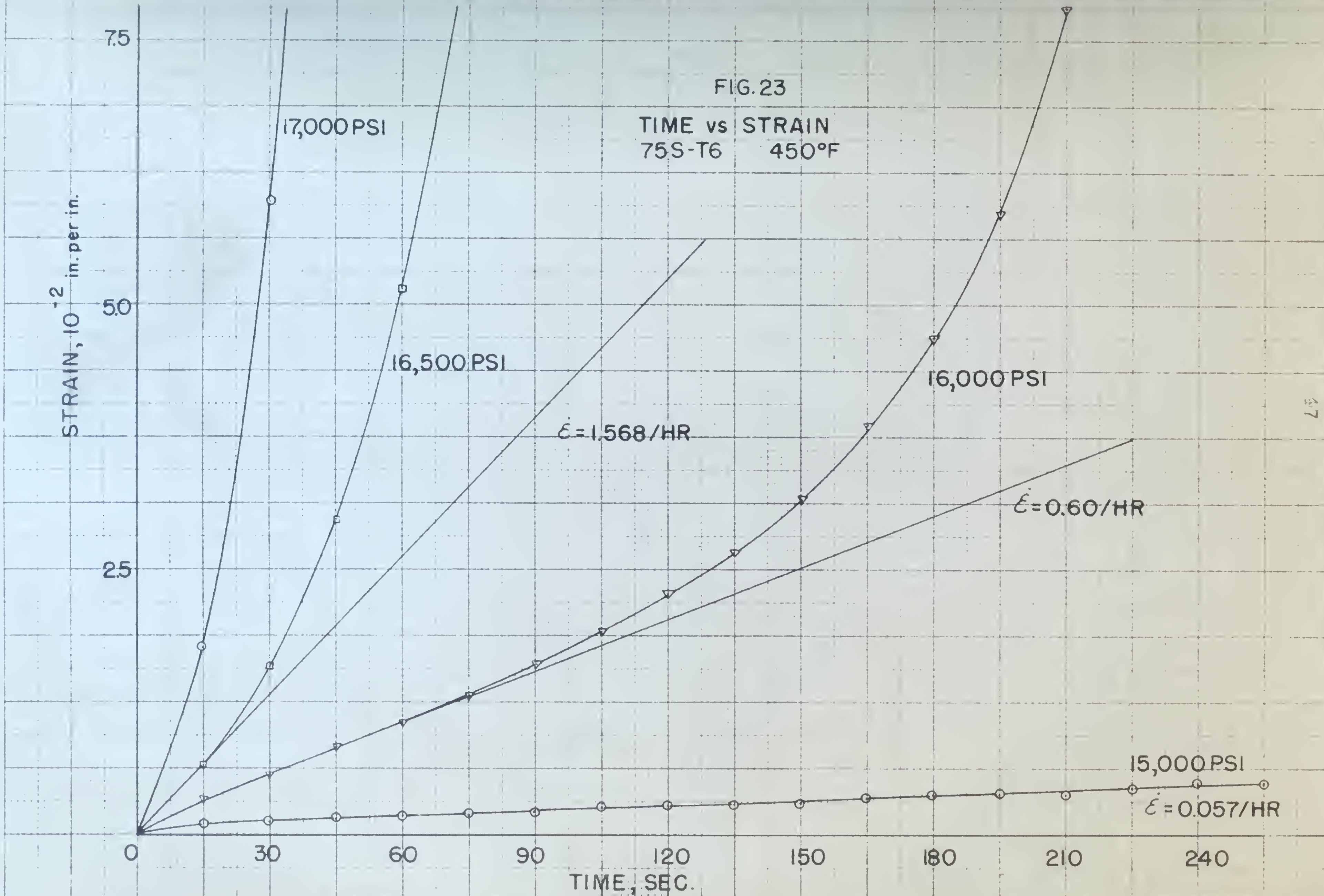


FIG. 22
TIME vs DEFORMATION
FS-1 500° F
GAGE LENGTH 4"

FIG. 23


TIME vs STRAIN
75S-T6 450°F
17,000 PSI
16,500 PSI
16,000 PSI
15,000 PSI
$\dot{\varepsilon}$ = 1.568/HR
$\dot{\varepsilon}$ = 0.60/HR
$\dot{\varepsilon}$ = 0.057/HR
STRAIN, 10^{-2} in. per in.
7.5
5.0
2.5
0
30
60
90
120
150
180
210
240
TIME, SEC.

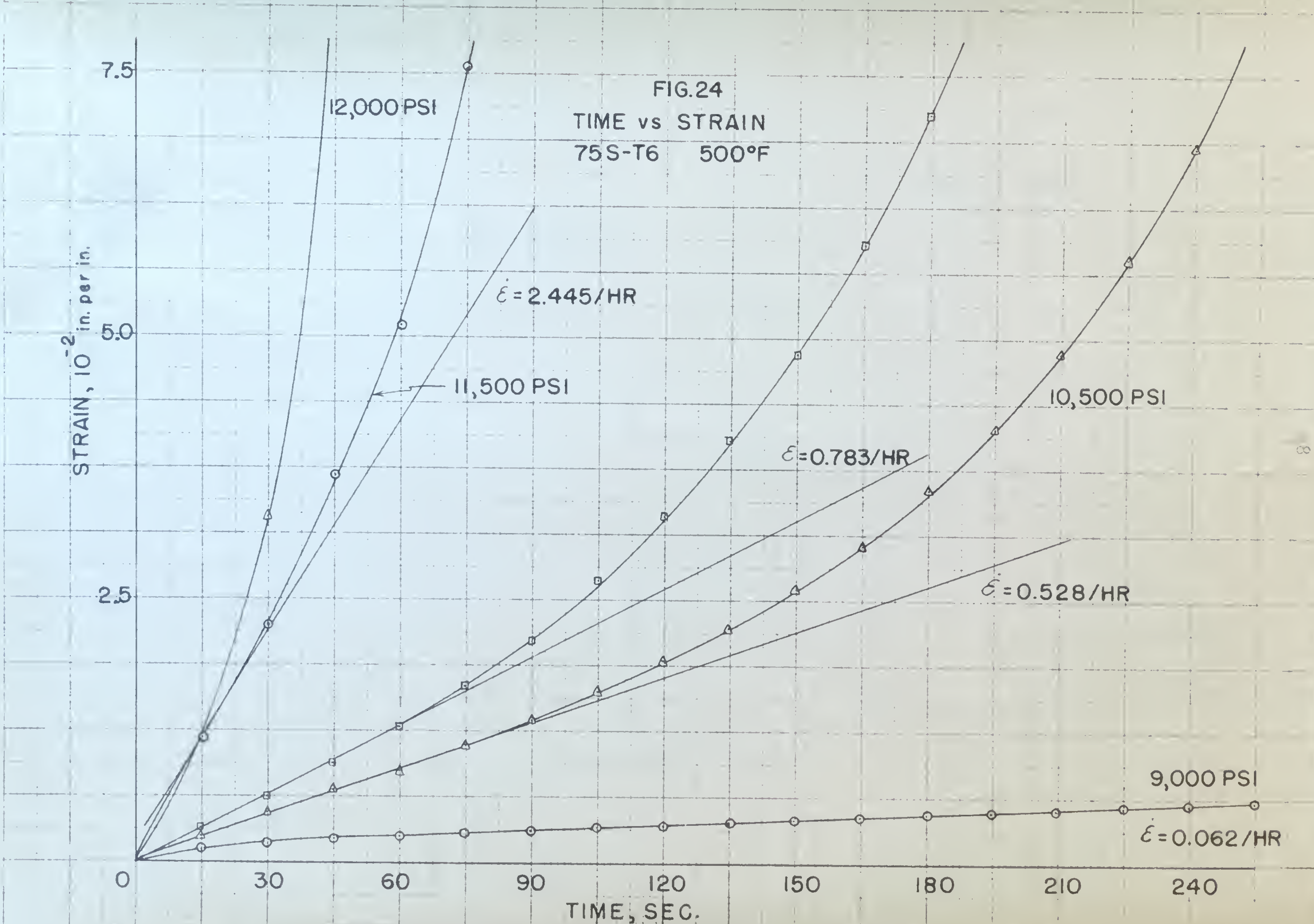


FIG.24
TIME vs STRAIN
75S-T6 500°F
12,000 PSI
11,500 PSI
10,500 PSI
9,000 PSI
$\dot{\varepsilon}$ = 2.445/HR
$\dot{\varepsilon}$ = 0.783/HR
$\dot{\varepsilon}$ = 0.528/HR
$\dot{\varepsilon}$ = 0.062/HR
STRAIN, 10^{-2} in. per in.
TIME, SEC.
0
2.5
5.0
7.5
30
60
90
120
150
180
210
240

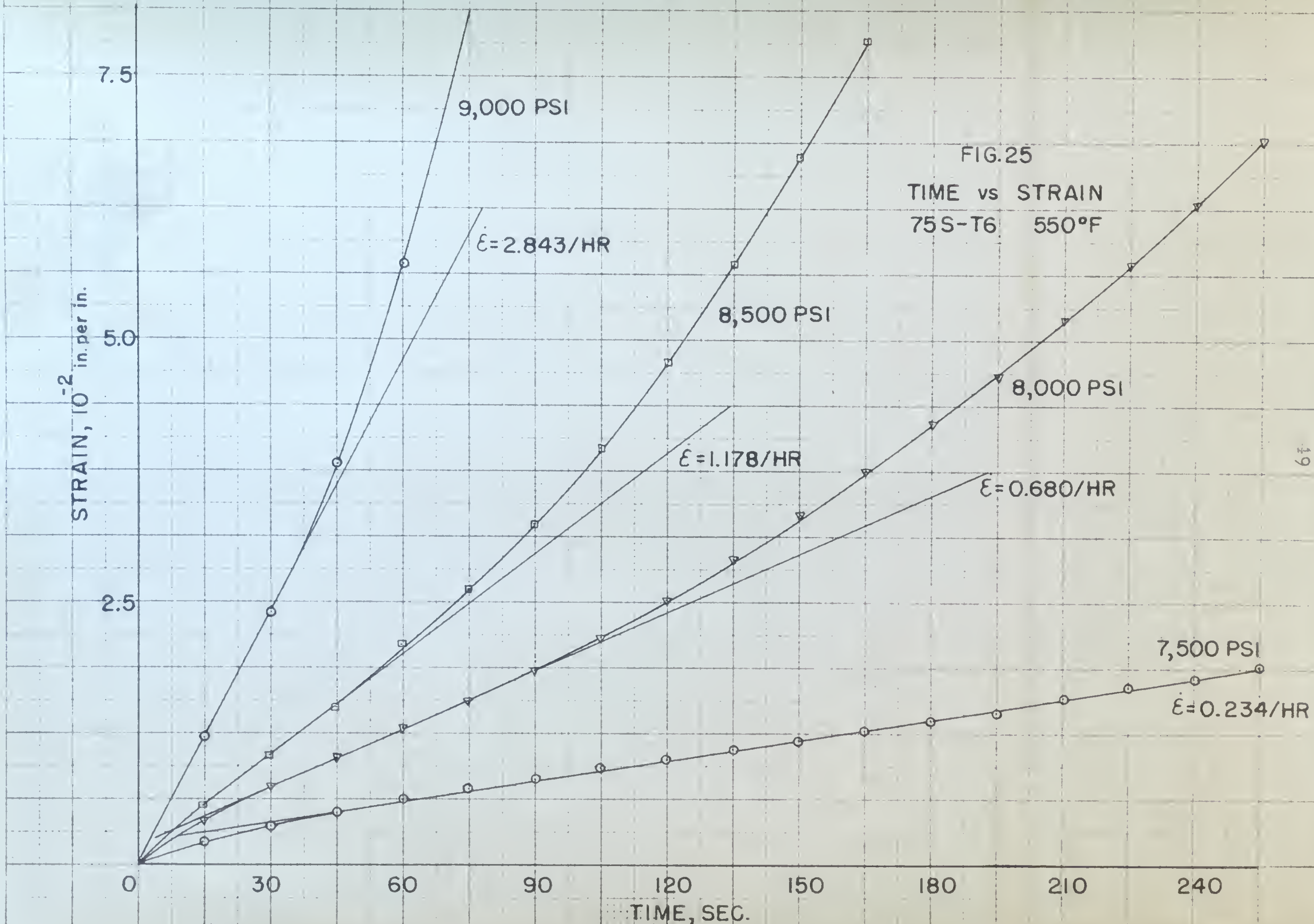


FIG. 25
TIME vs STRAIN
75S-T6 550°F

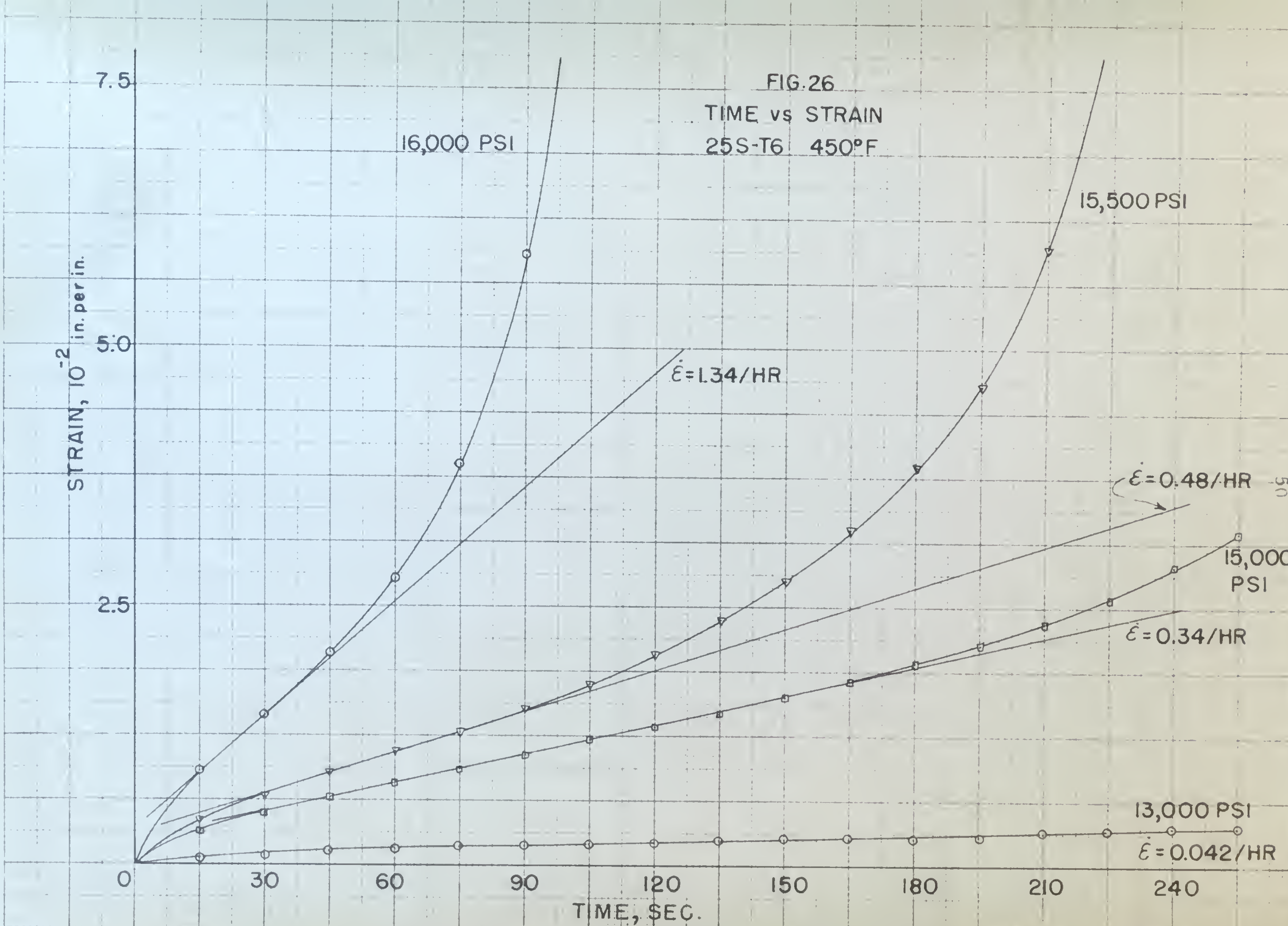


FIG. 26
TIME vs STRAIN
25S-T6 450°F
16,000 PSI
15,500 PSI
$\dot{\varepsilon}$=1.34/HR
$\dot{\varepsilon}$=0.48/HR
15,000 PSI
$\dot{\varepsilon}$=0.34/HR
13,000 PSI
$\dot{\varepsilon}$=0.042/HR
STRAIN, 10^{-2} in. per in.
7.5
5.0
2.5
0
30
60
90
120
150
180
210
240
TIME, SEC.

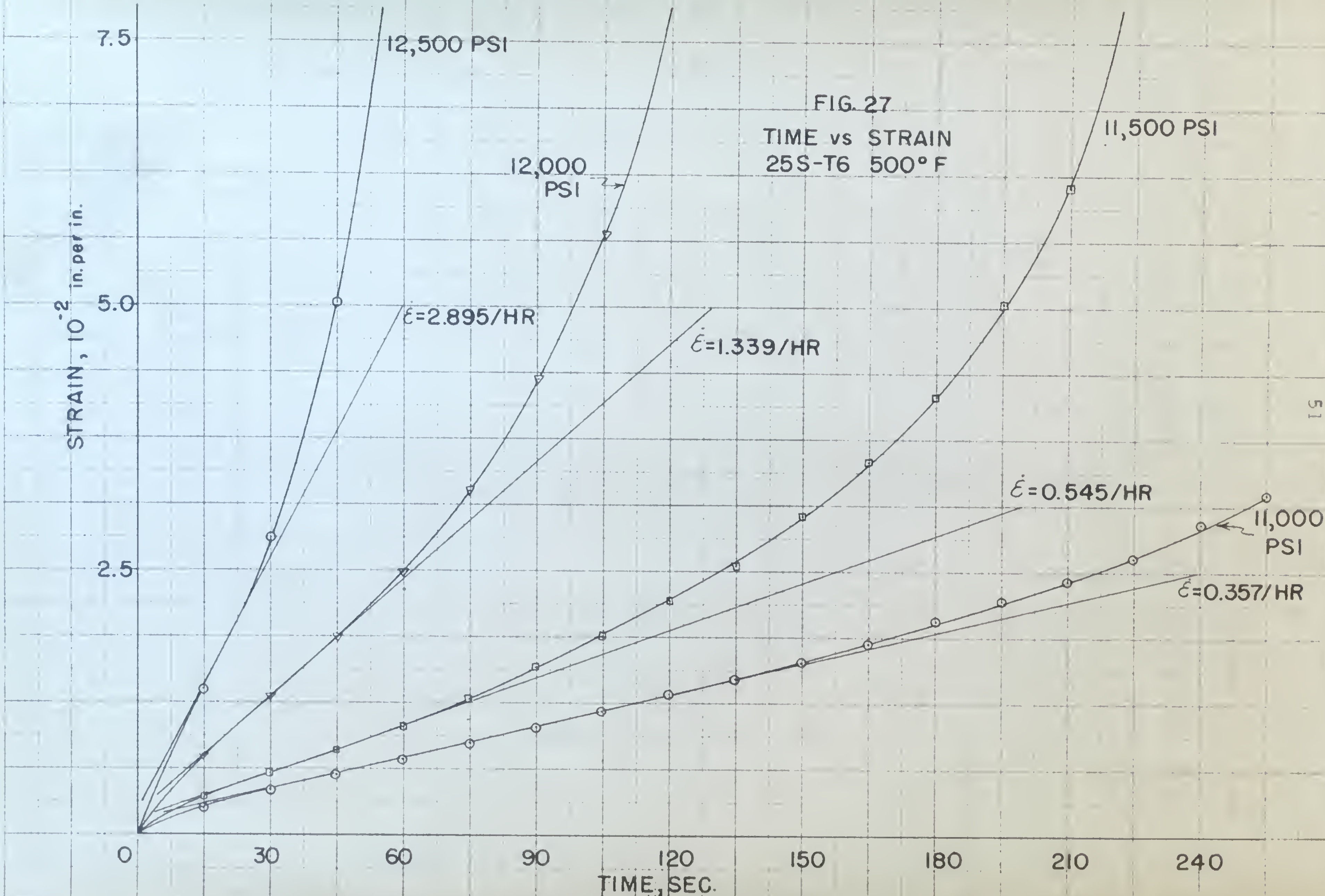


FIG. 27
TIME vs STRAIN
25S-T6 500° F
12,500 PSI
12,000 PSI
11,500 PSI
11,000 PSI
Ė=2.895/HR
Ė=1.339/HR
Ė=0.545/HR
Ė=0.357/HR
STRAIN, 10⁻² in. per in.
TIME, SEC.
0
30
60
90
120
150
180
210
240
2.5
5.0
7.5

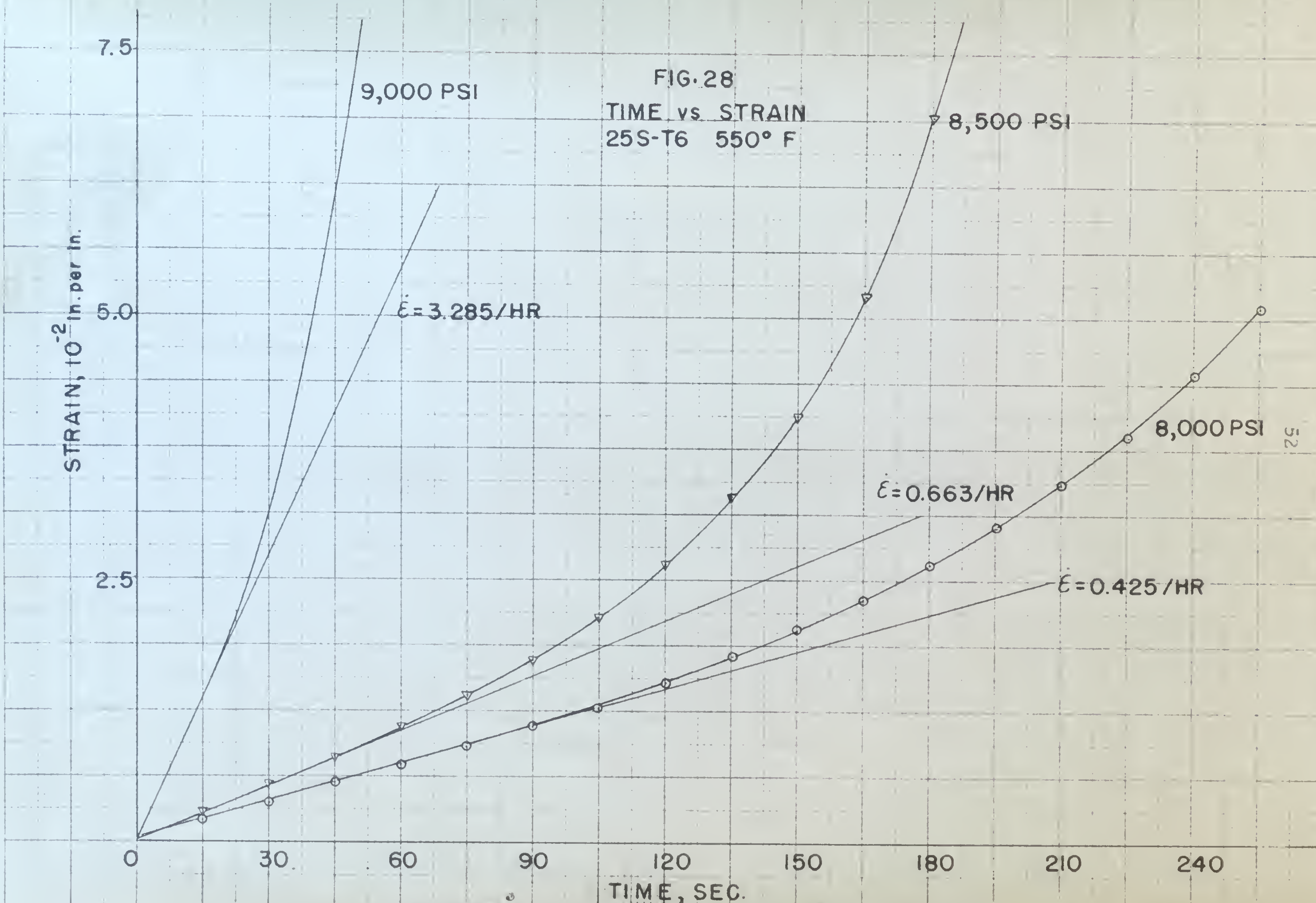


FIG. 28
TIME vs STRAIN
25S-T6 550° F

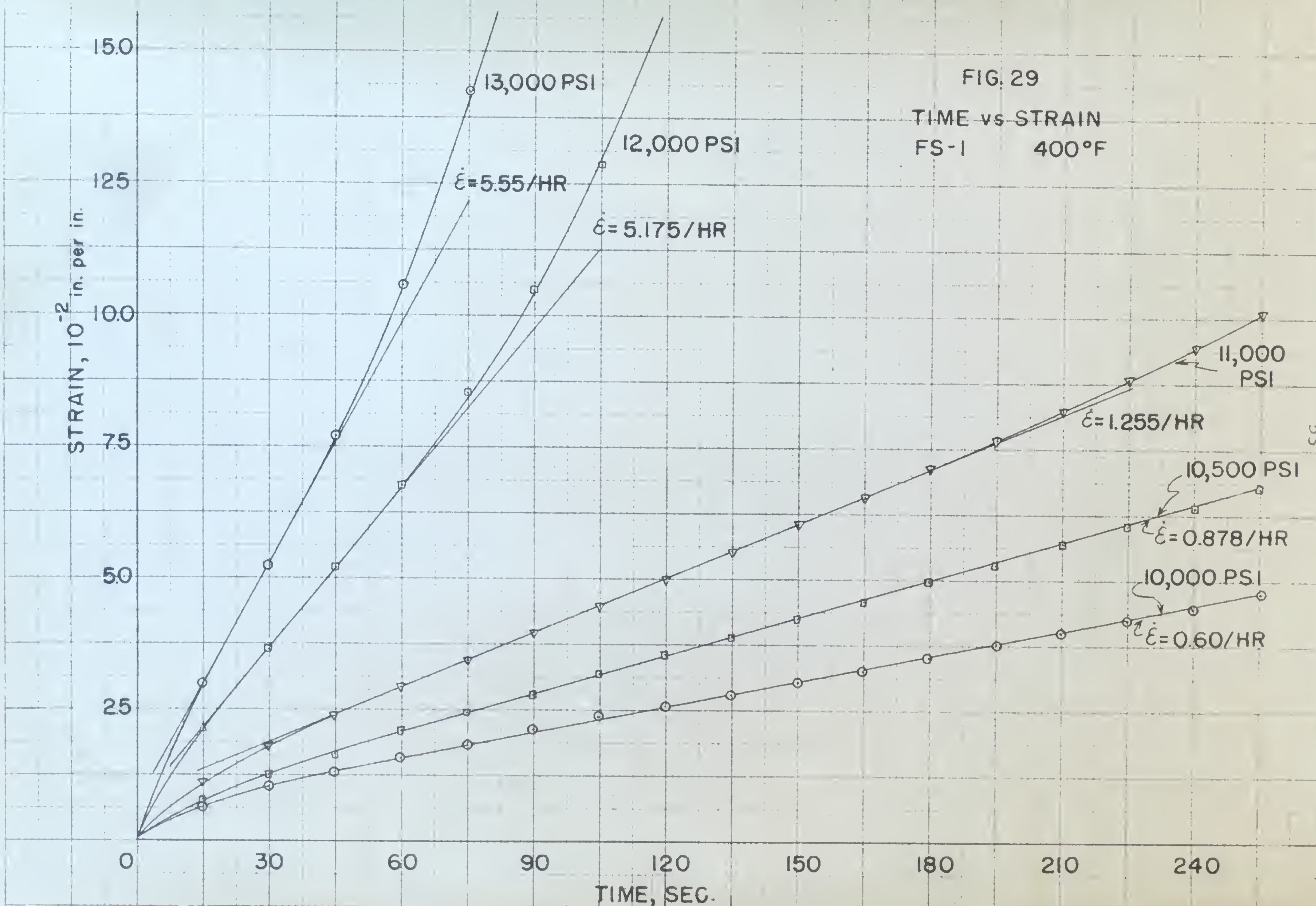


FIG. 29
TIME vs STRAIN
FS-1 400°F
13,000 PSI
12,000 PSI
$\dot{\varepsilon}$=5.55/HR
$\dot{\varepsilon}$= 5.175/HR
11,000 PSI
$\dot{\varepsilon}$=1.255/HR
10,500 PSI
$\dot{\varepsilon}$= 0.878/HR
10,000 PSI
$\dot{\varepsilon}$= 0.60/HR
STRAIN, 10^{-2} in. per in.
15.0
125
10.0
7.5
5.0
2.5
0
30
60
90
120
150
180
210
240
TIME, SEC.

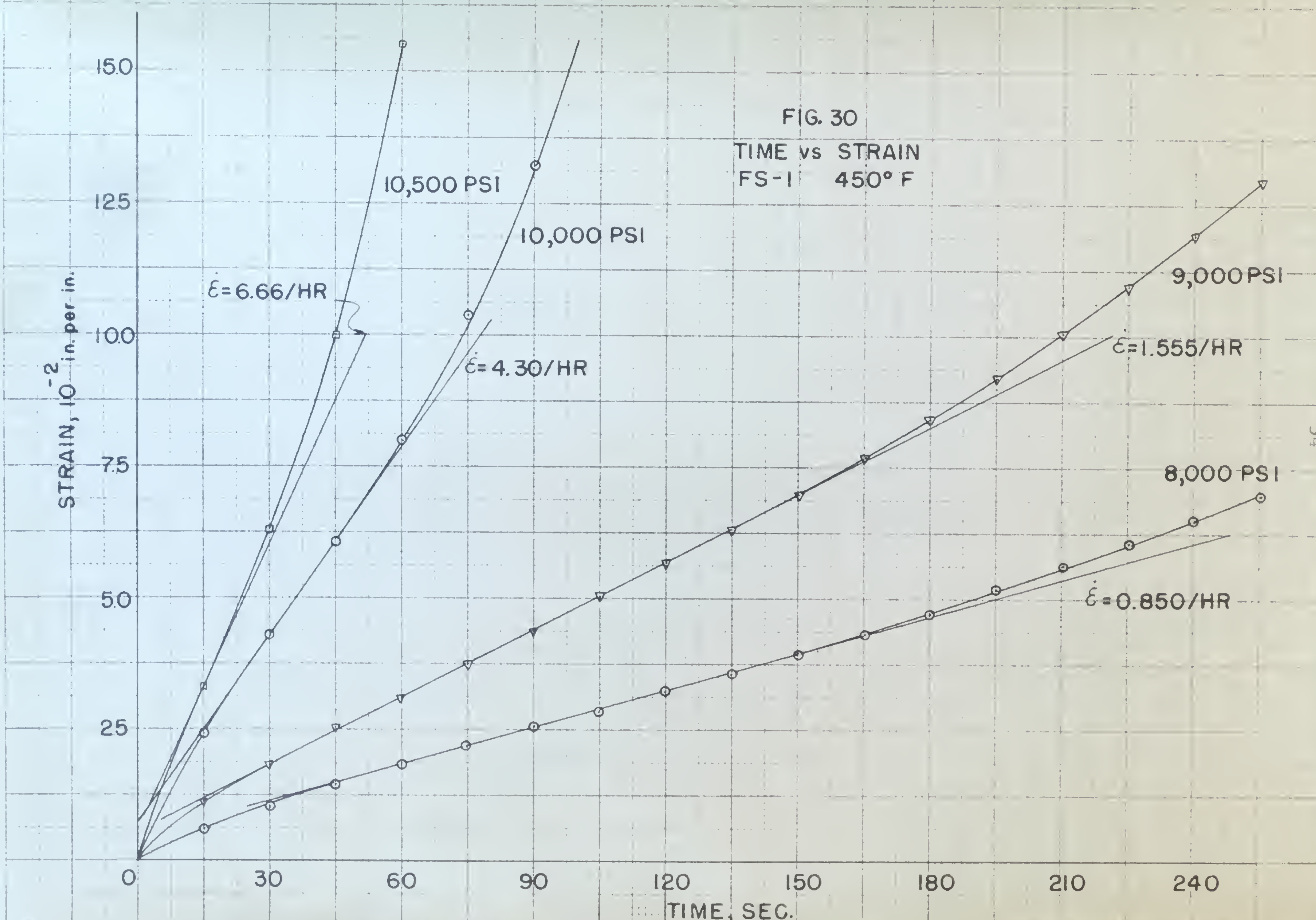


FIG. 30
TIME vs STRAIN
FS-1 450° F
10,500 PSI
10,000 PSI
9,000 PSI
8,000 PSI
$\dot{\varepsilon}$=6.66/HR
$\dot{\varepsilon}$=4.30/HR
$\dot{\varepsilon}$=1.555/HR
$\dot{\varepsilon}$=0.850/HR
STRAIN, 10^{-2} in. per in.
15.0
12.5
10.0
7.5
5.0
2.5
0
30
60
90
120
150
180
210
240
TIME, SEC.

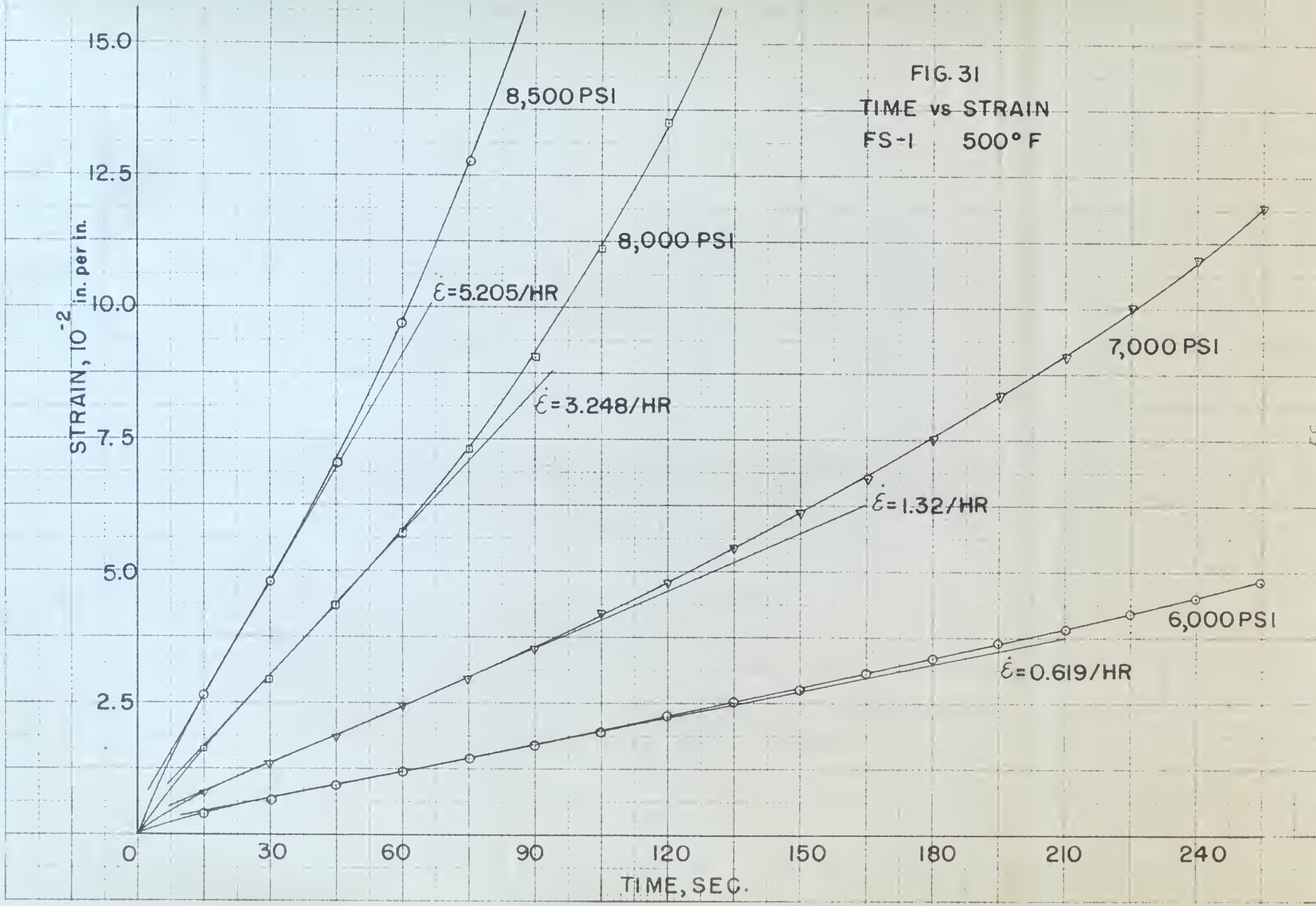


FIG. 31
TIME vs STRAIN
FS-1 500° F
8,500 PSI
8,000 PSI
7,000 PSI
6,000 PSI
$\dot{\varepsilon}$=5.205/HR
$\dot{\varepsilon}$=3.248/HR
$\dot{\varepsilon}$=1.32/HR
$\dot{\varepsilon}$=0.619/HR
STRAIN, 10^{-2} in. per in.
TIME, SEC.
0
30
60
90
120
150
180
210
240
2.5
5.0
7.5
10.0
12.5
15.0

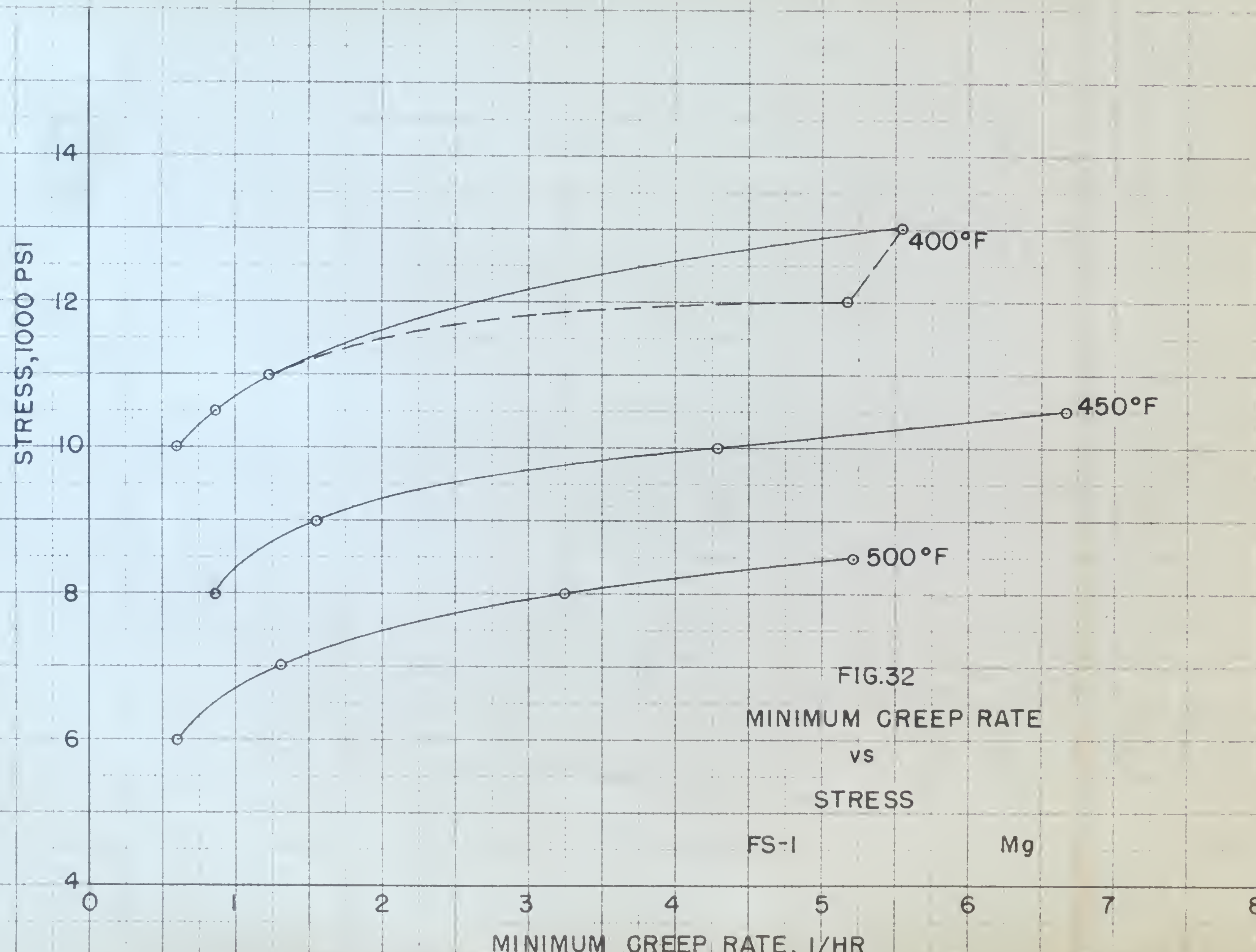
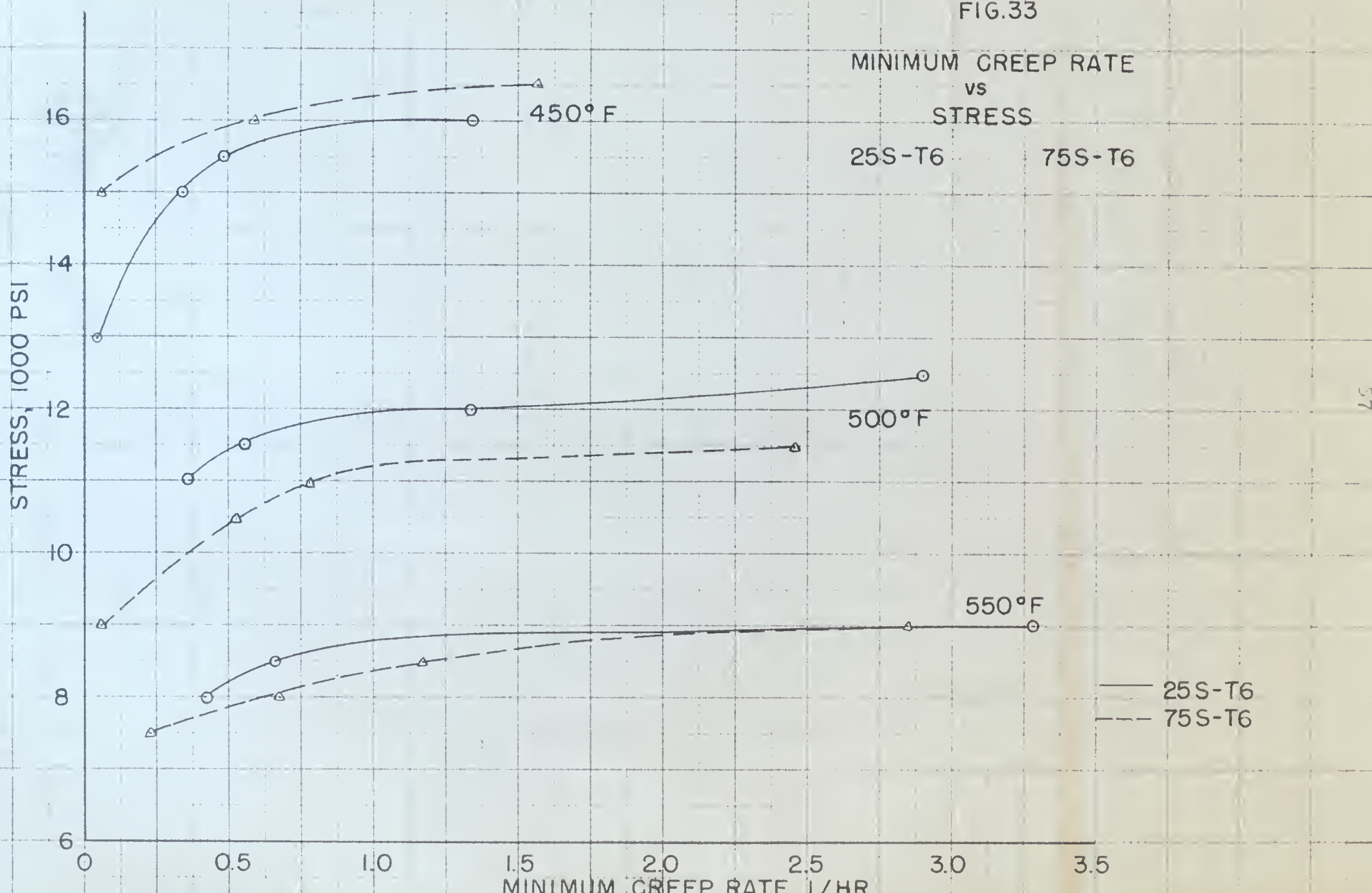


FIG.32
MINIMUM CREEP RATE
vs
STRESS

FIG.33

MINIMUM CREEP RATE vs STRESS

25S-T6 75S-T6



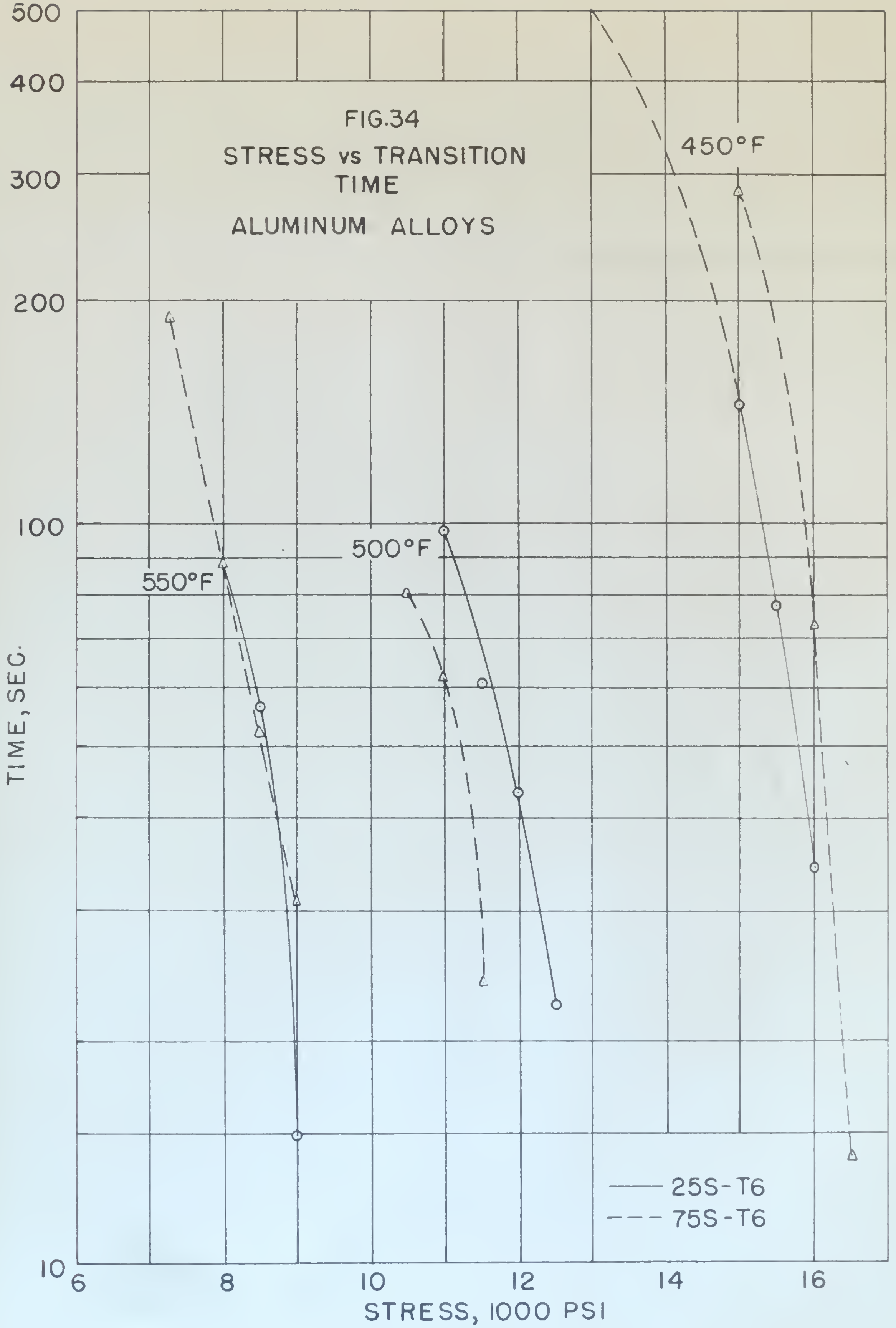


FIG.34
STRESS vs TRANSITION TIME
ALUMINUM ALLOYS
450°F
500°F
550°F
25S-T6
75S-T6
TIME, SEC.
STRESS, 1000 PSI
500
400
300
200
100
10
6
8
10
12
14
16

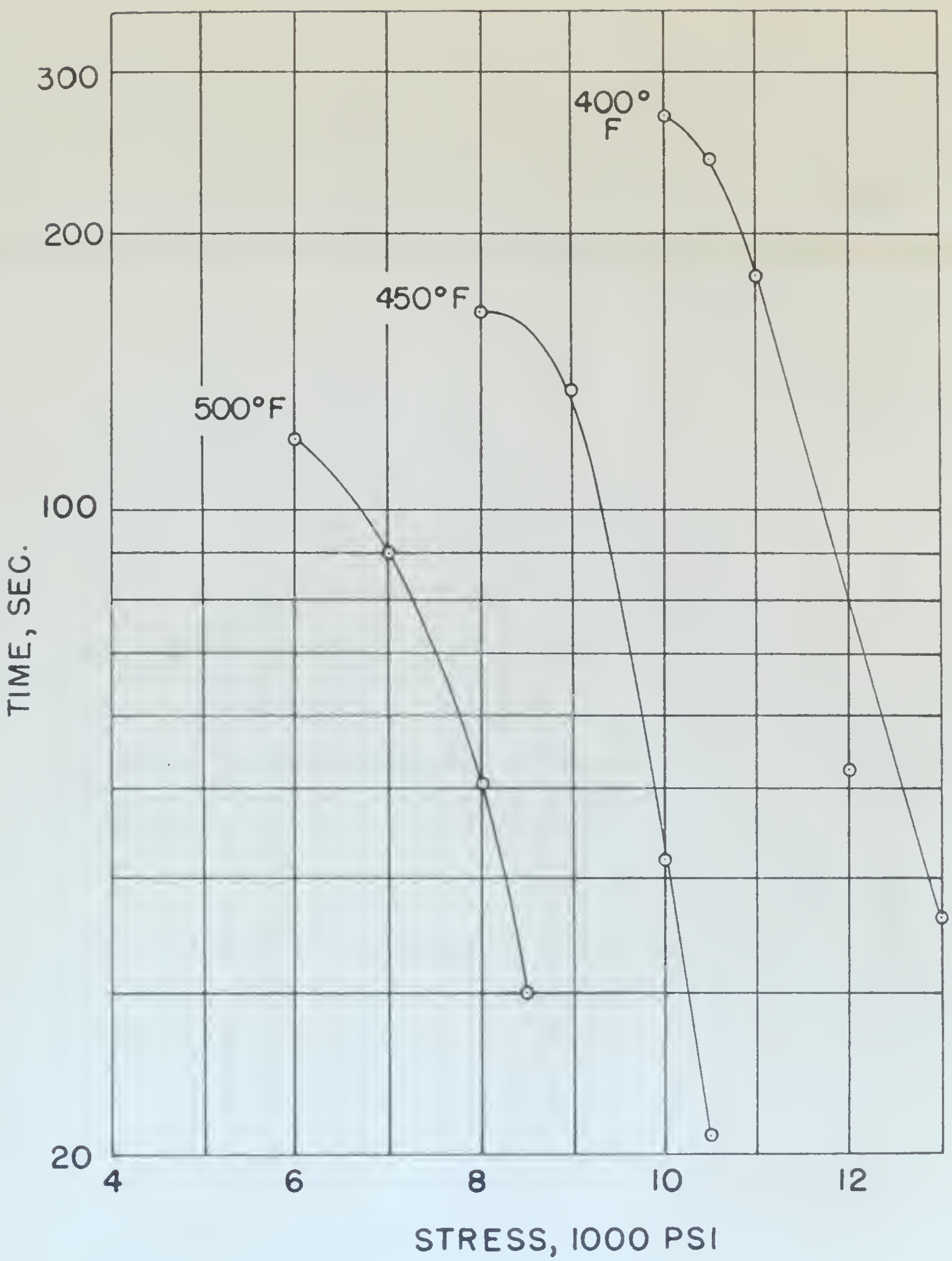


FIG. 35

STRESS vs TRANSITION TIME

FS-1 Mg

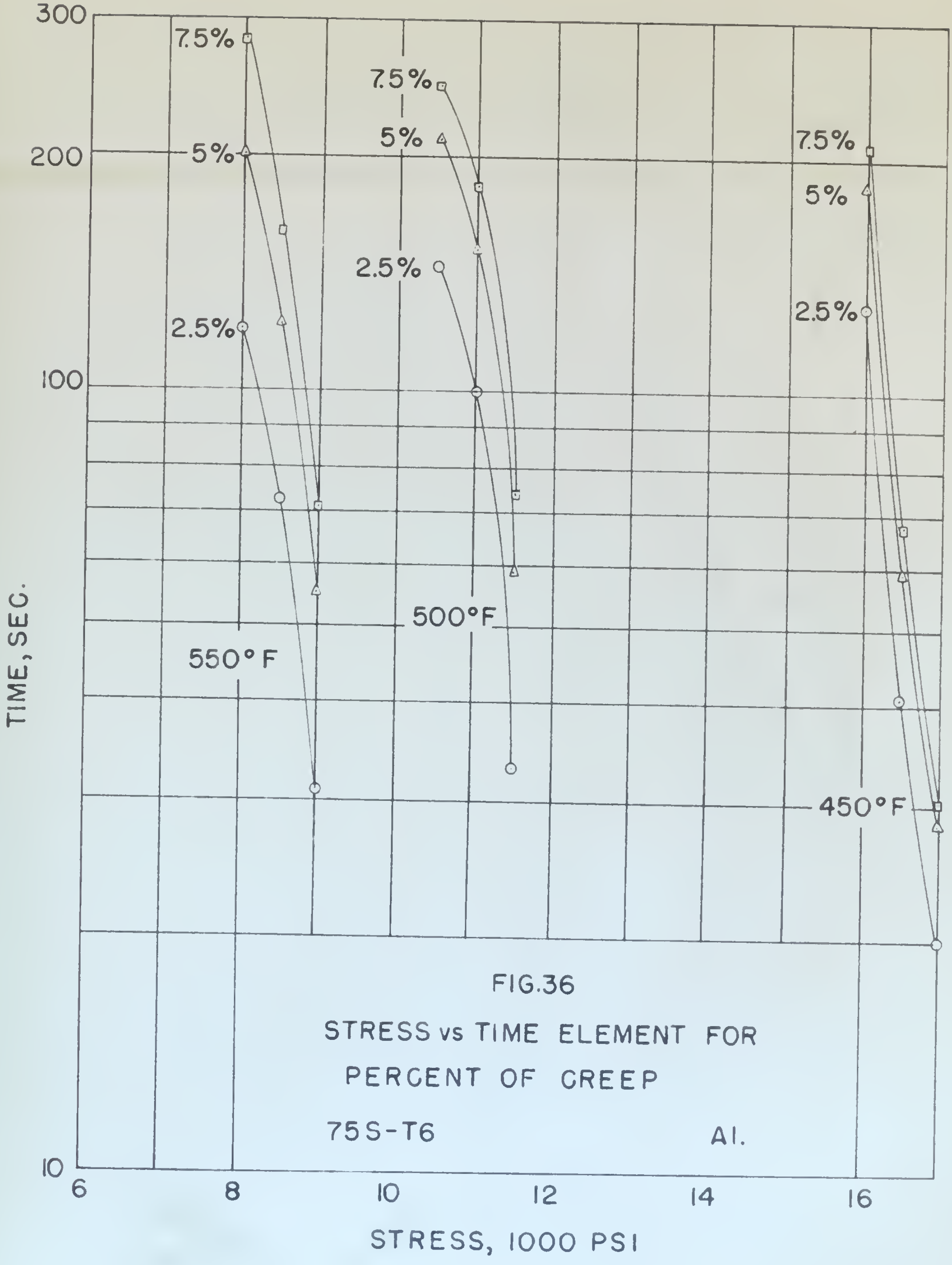


FIG.36

STRESS vs TIME ELEMENT FOR PERCENT OF CREEP

75S-T6 Al.

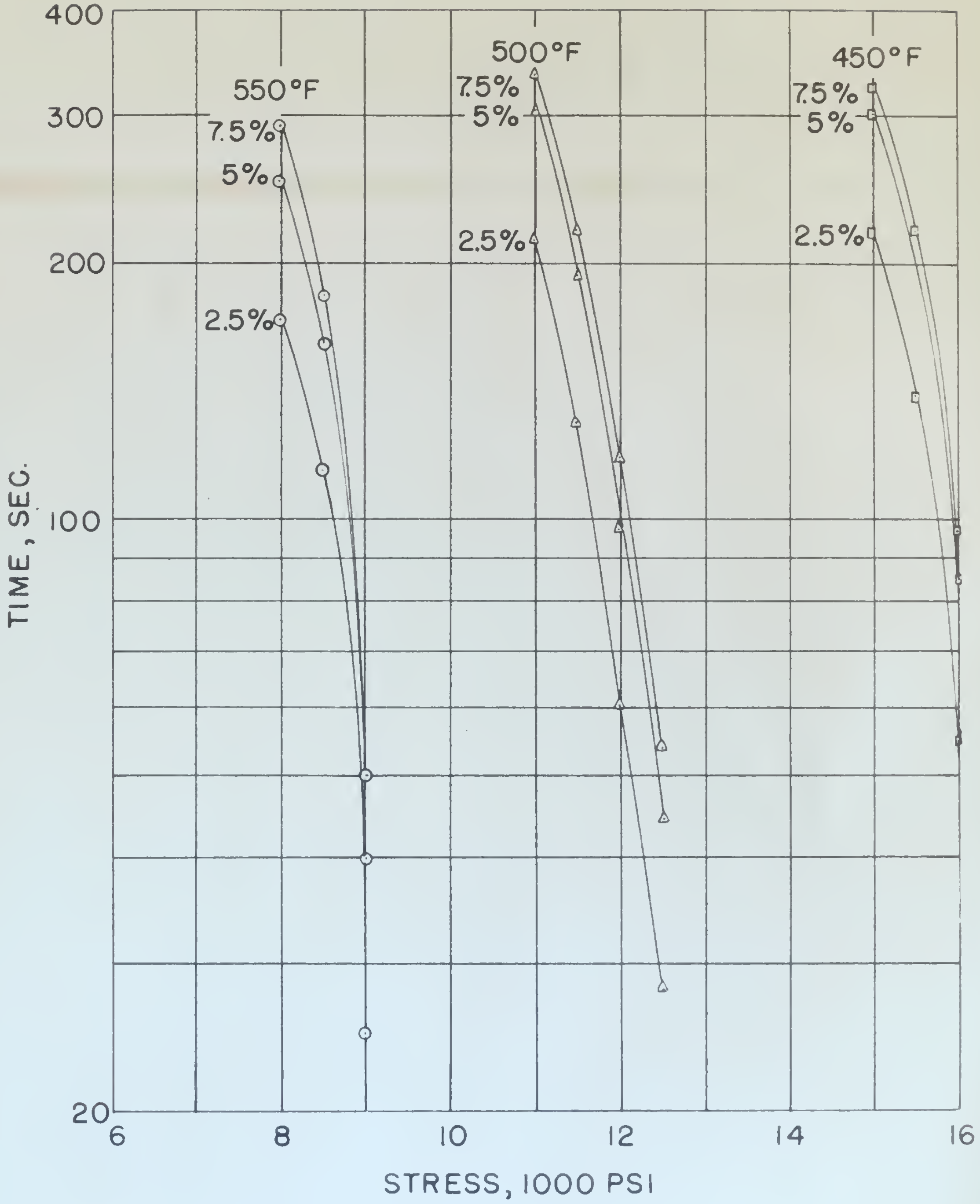


FIG.37

STRESS vs TIME FOR PERCENT OF CREEP

25 S-T6 Al.

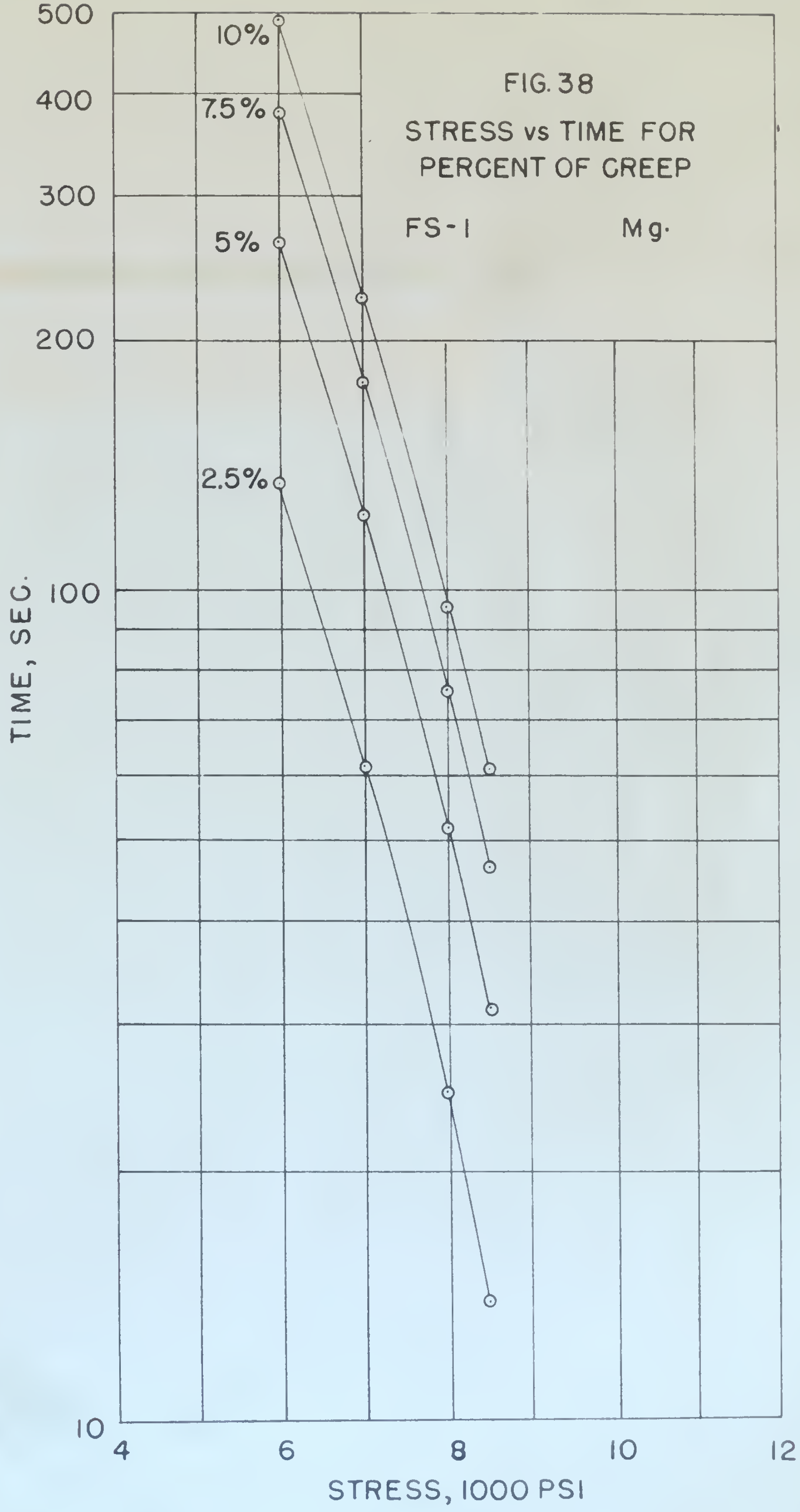


FIG. 38
STRESS vs TIME FOR
PERCENT OF CREEP
FS-1
Mg.
10%
7.5%
5%
2.5%
500
400
300
200
100
10
4
6
8
10
12
TIME, SEC.
STRESS, 1000 PSI